GEOPHYSICS

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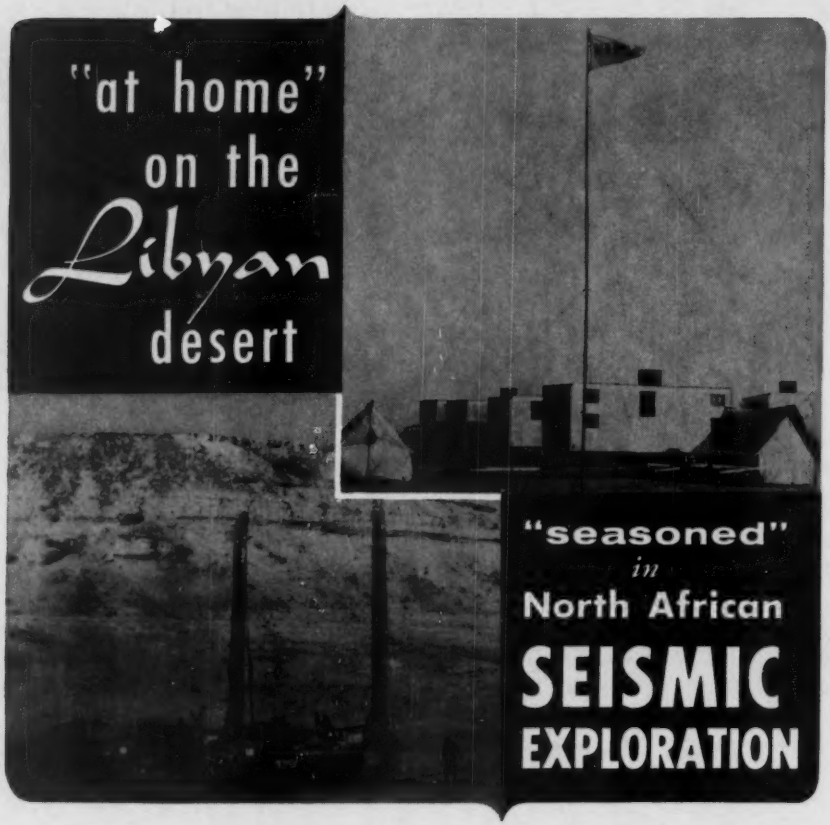

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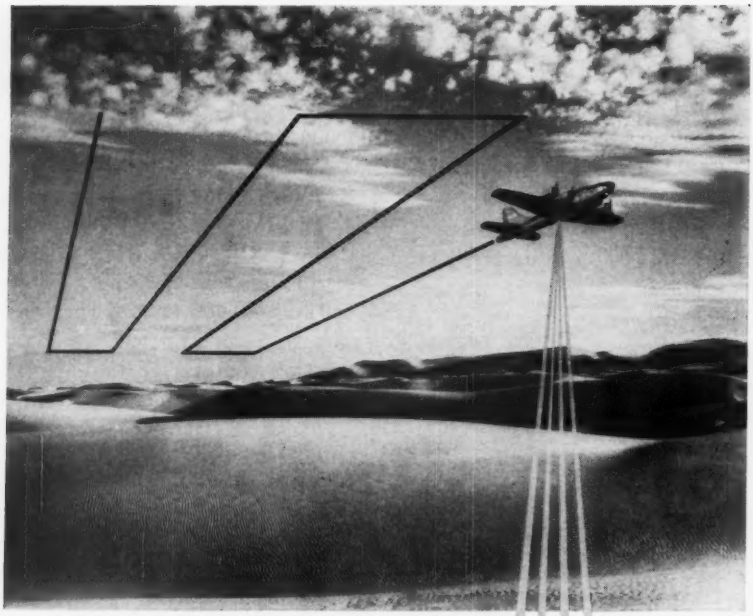

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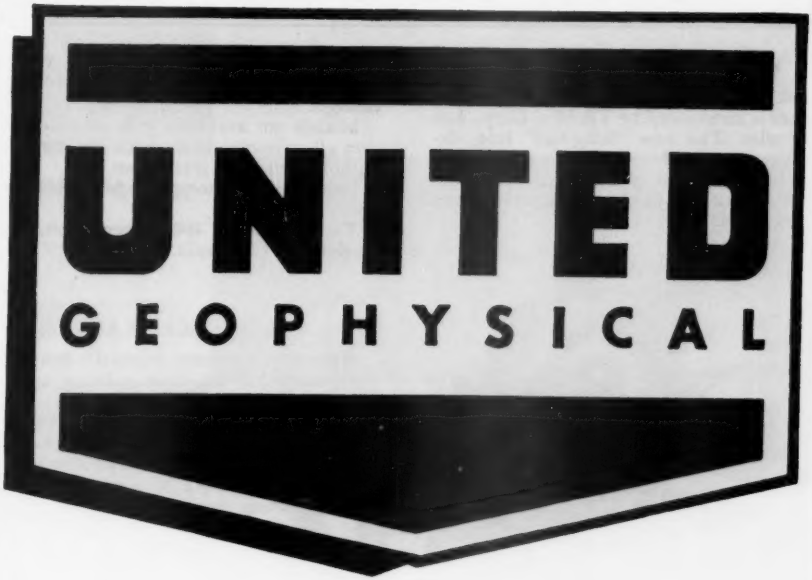

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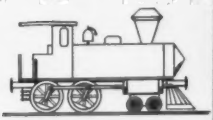

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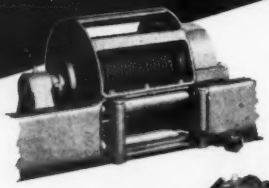

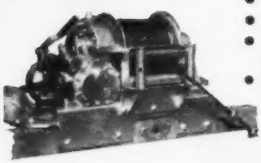

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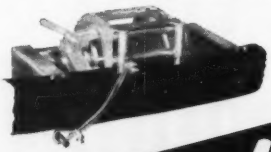

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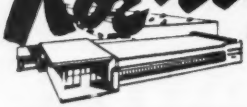

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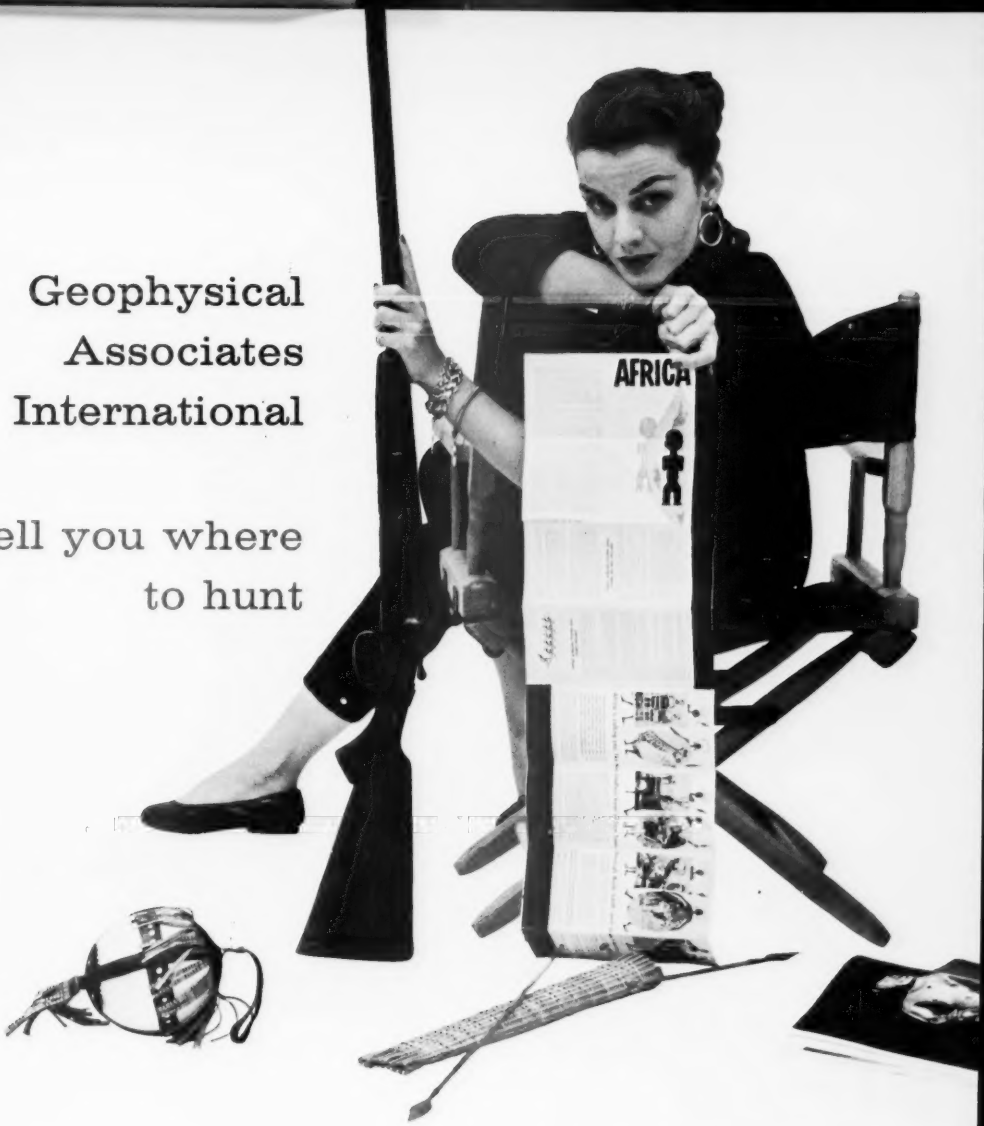

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GEOPHYSICS

EDITORIAL

SEG INSTITUTIONS—THEIR CONTINUED IMPROVEMENT

SEG has developed two institutions of world-wide scientific importance—GEOPHYSICS and the Annual Meeting. The Twenty-Ninth Annual Meeting of the Society of Exploration Geophysicists will convene at Los Angeles on November 9, 1959.

The annual meetings have increased in stature in recent years. The large number of high quality papers, the concurrent Mining Geophysics sessions, and most important, the development of the Research sessions have been significant milestones in our progress. These accomplishments, requiring additional sessions and additional auditorium facilities, were possible only as a consequence of the SEG decision to discontinue joint annual meetings with AAPG Our pride in our two great institutions may be expressed most effectively by efforts toward further improvement.

The discontinuance of the joint annual meetings has deprived our membership of the opportunity to hear significant geological papers. We have suggested to the Program Chairman that a group of geological papers be included in our general sessions. To assure that these are papers of interest to geophysicists, they should be invited papers,[1] selected primarily from the preceding AAPG Convention.

Many of us are aware of the need for general improvement in the presentation of papers. The Best Presentation Award (see page 862 for details) will be bestowed for the first time this year, and is designed to encourage better delivery. We hope that the suggestions for preparing an oral presentation (Faust, 1958) will be considered seriously by the authors and will aid them.

Pimm (1959) deplored the unsatisfactory arrangement and consequent poor attendance at the session devoted to the Presidential Address, to the addresses of the invited speakers, and to the presentation of Honors and Awards. In reponse to his criticisms the Vice President and the Los Angeles Committees have designed a superior plan. The invited speakers will be given places of honor on the program, but will no longer be grouped sequentially. The Honors and Awards are scheduled for presentation at a luncheon meeting. We feel assured that these

[1] Lack of sufficient auditorium facilities at Los Angeles will prevent the Program Chairman, Mr. Braun, from following this suggestion to the extent he would prefer.

arrangements will receive the support of the membership by a large attendance.

These efforts toward improvement of our Annual Meeting should result in the forthcoming Los Angeles Meeting surpassing all previous meetings in quality. We suggest that those in attendance can aid in improving another deficiency.

A considerable amount of valuable information is lost through failure of the authors to seek publication in GEOPHYSICS. Less than 20 percent of the papers presented at San Antonio in October 1958 have been submitted to the Editor to date (July 1, 1959). A few have been published elsewhere by special arrangements. Past experience suggests that less than 50 percent will ever be submitted for publication. SEG Policy (1958), published repeatedly, states:

"When a paper is accepted for presentation at an annual or regional meeting of the Society, its author is ordinarily expected to submit within a reasonable time, a manuscript of the paper for possible publication in GEOPHYSICS."

Since this requirement is presumably known to our authors we must accept their non-compliance as a fact for which we should seek a remedy. Perhaps not only the author, but also his audience is at fault.

The average author presents his paper because he believes it is significant. He is proud of his work and seriously interested in it. He hopes to elicit discussion and suggestions from other investigators in the same field. Too often the discussion period following the paper is notable for its silence. This may be understandable since many of us are loath to offer comments extemporaneously. Previously prepared discussions are a partial answer, but the mechanics of our meetings are such that, except in the Research sessions, there is insufficient time for a long discussion period. There is however another type of discussion possibly more important to the author—the informal discussion. It is not unusual to find our more experienced speakers stationed outside the doors of the auditorium immediately following their presentations. They are making themselves available for questions, criticisms, suggestions, and comments. The exchange of ideas with other interested investigators is often the chief reward to the author for his work. The author who receives no evidence of interest may conclude that his subject is unimportant and so loses the incentive for the difficult task of preparing his paper for publication.

We suggest that the audience at the forthcoming convention has a duty to perform. Those not inclined to comment publicly on a paper of interest might seek out the author afterwards. They as well as the author will enjoy and profit by discussion. Those who believe a paper should appear in GEOPHYSICS should so advise the author.

The material appearing in GEOPHYSICS should be governed to a considerable extent by the interests of the membership. We believe that members attending our annual meeting have the right and the duty to encourage submission to GEOPHYSICS of those papers they consider worthy. Is it possible that the statistics on the submission of papers to GEOPHYSICS has been indeed a function of the exercise, deliberate or otherwise, of that right?

We emphasize that an author has a duty to his Society as well as to himself to submit his manuscript for possible publication. Failure to do so results in a loss to our science. It is the responsibility of the audience to aid the authors by discussions either formal or informal. If the members of the audience express to the author a desire to see his paper in print, they encourage him to prepare this manuscript and remind him of his obligation to do so.

THE EDITOR

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GEOPHYSICS, VOL. XXIV, NO. 4 (OCTOBER, 1959), PP. 658–666, 3 FIGS.

WAVE PROPAGATION IN A LIQUID LAYER*

D. T. LIU†

ABSTRACT

In many areas offshore, the conventional seismic record has the appearance of a series of sine waves or simple odd harmonic combinations of sine waves, with a fundamental wave length four times the water depth. Burg, et al., in a ray theory treatment, ascribe this oscillatory phenomenon to guided energy traveling in the water layer.

A solution of the pressure wave equation for a point source in the water layer has been obtained. It allows one to examine not only the frequency dependence with the depth, but also the transient amplitude response with depth and time.

It is concluded that in most actual situations, the phenomenon cannot be wholly explained by the assumed mechanism, because the theory indicates too rapid a decay of the energy.

In a number of areas offshore, the conventional seismic record has the appearance of sine waves, or of simple odd harmonic combinations of sine waves, with a fundamental wave length four times the water depth. This phenomenon can appear on seismic records in varying degrees from the extreme form when the oscillation occurs throughout the record all the way down to reasonably good records. The reflection events are often masked by the oscillation, and picking of events is very questionable, if not impossible.

As a first step toward a better understanding of this oscillatory phenomenon, it is worthwhile to examine theoretically the propagation of explosive sound in the water layer. Our problem is to determine the pressure field in the water due to a point source located at a depth d below the water surface.

For purposes of analysis we assume that the water layer is a perfect acoustic medium of density ρ_1 and sound velocity c_1, which is overlying a semi-infinite acoustic medium of density ρ_2 and velocity c_2 (Fig. 1).

The pressure field is determined by the wave equation

$$\nabla^2 p = \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} \tag{1}$$

where p is the pressure, and the particle velocity in terms of pressure is

$$\text{grad } p = -\rho \frac{\partial \vec{u}}{\partial t}$$

where $\vec{u}$ is the velocity vector. A subscript 1 or 2 will be used to designate the given quantity in the upper or lower medium respectively.

In order to find the frequency dependence on the depth, we will solve equa-

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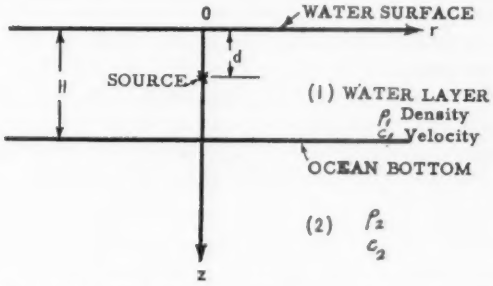

FIG. 1. Mathematical model for a two-layered acoustic medium.

tion (1) subject to the following conditions:

$$p_1 = 0 \quad \text{at} \quad z = 0, \tag{2}$$

$$\frac{\partial p_1}{\partial z} = 0 \quad \text{at} \quad z = H, \tag{3}$$

and a sinusoidal pressure field of the form

$$p_0(R) = \frac{1}{R} e^{i(kR-\omega t)} \tag{4}$$

radiates from the point (o, d), where $R^2 = r^2 + (z-d)^2$, and $k = \omega/c_1 =$ wave number.

The condition (3) implies that the bottom is perfectly rigid, so that no energy can escape through it. This condition is used here to simplify the mathematics, as the frequency dependence is primarily determined by the geometry of the system. However, in a later stage we will remove this restriction in favor of a non-rigid liquid layer to simulate an absorptive ocean bottom.

The steady state solution of the pressure wave equation that satisfies the conditions (2), (3), and (4) is straight forward. Instead of writing down the result immediately we will build up the solution from the physical picture of images (Fig. 2). If we add all the images and apply Poisson's formula (Titchmarsh, 1948), the pressure distribution off the axis becomes:

$$p_1(r, z, t) = \frac{2\pi i}{H} \sum_{n=0}^{\infty} \sin\left(n + \frac{1}{2}\right)\frac{\pi d}{H} \sin\left(n + \frac{1}{2}\right)\frac{\pi z}{H} H_0^{(1)}(\alpha_n r) e^{-i\omega t} \tag{5}$$

where

$$\alpha_n = \left[k^2 - \left(n + \frac{1}{2}\right)^2 \frac{\pi^2}{H^2}\right]^{1/2}. \tag{6}$$

$H_0^{(1)}$ denotes the Hankel function of zero order and first kind.

This is the "normal mode solution."

Now let us examine the physical meaning of the normal mode solution. First of all, the pressure field is a sum of normal modes. These are of different natures depending on whether $\alpha_n^2>0$ or $\alpha_n^2<0$. In the former case, the pressure becomes a progressive wave system, and the amplitude of the nth mode is weakened with the range through the cylindrical divergence factor $r^{-1/2}$. On the other hand, if $\alpha_n^2<0$, the argument of the Hankel function becomes an imaginary quantity. In this case, the amplitude of the nth mode suffers both cylindrical divergence and

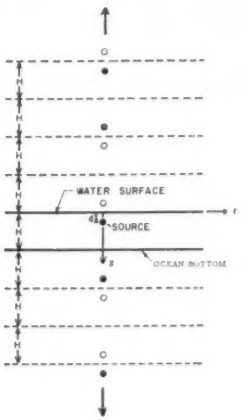

FIG. 2. Image method (● source, ○ source of the same strength but opposite phase).

an exponential attenuation with range r, and the wave does not propagate. Each normal mode has a lower cutoff frequency.

As a special case, when $\alpha_n^2=0$, the Hankel function approaches infinity, indicating a "resonance." The corresponding frequencies are

$$f_n = \frac{(2n+1)c_1}{4H}, \qquad n = 0, 1, 2, \cdots$$

The resonant condition is analogous to that of an organ pipe closed at one end. This frequency-depth relationship checks with many observed oscillatory seismograms. In this solution, the pressure approaches infinity at the "resonant frequency" for all values of the range r, because one has not introduced any absorptive mechanism, such as an absorptive bottom. But the pressure approaches infinity logarithmically, since the Hankel function has a logarithmic singularity at the origin. This infinity is very weak, and consequently the resonance phenomenon is weak. In fact, it is much weaker than a simple, nondissipative resonant electric circuit which approaches infinity as $(f-f')^{-1}$ when f approaches the resonant frequency f'. In actual practice, the resonance will be

weakened still further by dissipation in the medium and absorption by the bottom.

In order to obtain some amplitude information, one must deal with the transient pressure response in the water layer. Pekeris (1948) thoroughly investigated the dispersive wave phenomenon at very long ranges. Press and Ewing (1950) extended Pekeris' treatment of the case of a solid bottom. Both papers essentially dealt with rays greater than the critical angle. These rays form a dispersive progressive wave and travel in the water layer to a very long distance. In offshore seismic prospecting we usually operate at comparatively short ranges. Observation on conventional offshore seismograms indicates that dispersion is very gradual. The oscillation is a closely related phenomenon involving more nearly vertical incidence (Burg, etc., 1950). From this it follows that one can make an estimate of the transient pressure amplitude response in the water for the normal seismic spread, if the axial response due to the shot is known.

The transient solution of the pressure response at an axial point due to a pressure source $F(t)$ can be obtained by the method of Laplace transformation.

The problem consists of solving the pressure wave equation, in cylindrical coordinates,

$$\nabla^2 p_i = \frac{1}{c_i^2} \frac{\partial^2 p_i}{\partial t^2}, \qquad i = 1, 2 \tag{7}$$

subject to the following boundary conditions:

$$\text{(a)} \qquad p_1 = 0 \qquad \text{at } z = 0, \tag{8}$$

$$\text{(b)} \qquad p_1 = p_2 \qquad \text{at } z = H, \tag{9}$$

$$\text{(c)} \qquad \frac{1}{\rho_1} \frac{\partial p_1}{\partial z} = \frac{1}{\rho_2} \frac{\partial p_2}{\partial z} \qquad \text{at } z = H, \text{ and} \tag{10}$$

(d) A pressure field of the form

$$p_0(R) = \frac{1}{R} F\left(t - \frac{R}{c_1}\right) \tag{11}$$

where

$$R^2 = r^2 + (z - d)^2$$

is radiated from the point (o, d). The subscripts 1 and 2 denote the regions 1 and 2, respectively (Figure 1).

Applying Laplace transform to equation (7), we have

$$\nabla^2 \bar{p}_i = \frac{s^2}{c_i^2} \bar{p}_i, \qquad i = 1, 2 \tag{12}$$

where

$$\bar{p}_i = \int_0^\infty e^{-st} p_i(r, z, t)dt. \tag{13}$$

Similarly, the boundary conditions become

$$\bar{p}_1 = 0 \qquad \text{at } z = 0, \tag{14}$$

$$\bar{p}_1 = \bar{p}_2 \qquad \text{at } z = H, \tag{15}$$

$$\frac{1}{\rho_1}\frac{\partial \bar{p}_1}{\partial z} = \frac{1}{\rho_2}\frac{\partial \bar{p}_2}{\partial z} \qquad \text{at } z = H, \text{ and} \tag{16}$$

$$\bar{p}_0(R) = \bar{F}(s)\frac{e^{-sR/c_1}}{R}. \tag{17}$$

The solution of equation (12) is

$$\bar{p}_1 = \bar{F}(s)\left[\frac{e^{-sR/c_1}}{R} - \frac{e^{-sR'/c_1}}{R'}\right] + \int_0^\infty A(\lambda)J_0(\lambda r)\sinh \alpha z d\lambda \tag{18}$$

in layer (1), and

$$\bar{p}_2 = \int_0^\infty B(\lambda)J_0(\lambda r)e^{-\beta z}d\lambda \tag{19}$$

in layer (2), where

$$R = [r^2 + (z-d)^2]^{1/2}, \qquad R' = [r^2 + (z+d)^2]^{1/2}$$
$$\alpha = [(s/c_1)^2 + \lambda^2]^{1/2}, \qquad \beta = [(s/c_2)^2 + \lambda^2]^{1/2}$$

$A(\lambda)$ and $B(\lambda)$ are arbitrary constants.

The choice of hyperbolic sine function in equation (18) automatically satisfies condition (14). The two terms in the square bracket of equation (18) represent the source and image.

Applying the Sommerfeld formulae,

$$\frac{e^{-sR/c_1}}{R} = \int_0^\infty \frac{\lambda}{\alpha} J_0(\lambda r)e^{-\alpha|z-d|}d\lambda,$$

and

$$\frac{e^{-sR'/c_1}}{R'} = \int_0^\infty \frac{\lambda}{\alpha} J_0(\lambda r)e^{-\alpha(z+d)}d\lambda$$

to equation (18), and using the conditions (15) and (16), we find

$$A(\lambda) = \frac{2\lambda e^{-\alpha H}\bar{F}(s)}{\alpha} \cdot \frac{\sinh \alpha d[1 - (\beta/\alpha)(\rho_1/\rho_2)]}{\cosh \alpha H + (\beta/\alpha)(\rho_1/\rho_2)\sinh \alpha H}. \tag{20}$$

Substituting equation (20) in equation (18), the pressure response may be formally represented by the following formula:

$$\bar{p}_1(r, z, s) = \overline{F}(s)\left[\frac{e^{-sR/c_1}}{R} - \frac{e^{-sR'/c_1}}{R'}\right] + 2\int_0^\infty \frac{\lambda e^{-\alpha H}\overline{F}(s)}{\alpha} \frac{\left(1 - \frac{\beta\rho_1}{\alpha\rho_2}\right)\sinh \alpha d \sinh \alpha z J_0(\lambda r)}{\cosh \alpha H + \left(\frac{\beta\rho_1}{\alpha\rho_2}\right)\sinh \alpha H} d\lambda. \quad (21)$$

The next step is to apply the inversion theorem to equation (21) and find the pressure response versus time. The inverse transform of the two terms within the square bracket is straight forward. They are simply

$$\frac{1}{R} F\left(t - \frac{R}{c_1}\right) - \frac{1}{R'} F\left(t - \frac{R'}{c_1}\right) \quad (22)$$

which are the direct arrivals from the source and image. The wave shapes are preserved. Their arrival times are respectively $t = R/c_1$ and $t = R'/c_1$. The inverse transform of the integral in equation (21) is very complicated. However, a closed form solution can be obtained, if we are interested in primarily the axial pressure response.

Therefore, we will confine our attention to the inverse transform of the integral of equation (21) for $r = 0$,

$$\bar{p}_c(0, z, s) = \int_0^\infty \frac{2\lambda e^{-\alpha H}\overline{F}(s)}{\alpha} \frac{\left[1 - \frac{\beta\rho_1}{\alpha\rho_2}\right]\sinh \alpha d \sinh \alpha z}{\cosh \alpha H + \left(\frac{\beta\rho_1}{\alpha\rho_2}\right)\sinh \alpha H} d\lambda. \quad (23)$$

Let us first make the following substitution

$$\lambda = su$$

in equation (23). Expressing the hyperbolic functions in the integrand in terms of exponential functions and expanding the inverse of the denominator, we get

$$\bar{p}_c(0, z, s) = \sum_{n=1}^{\infty} \sum_{m=1}^{4} (-1)^{n+m-1} \int_0^\infty \frac{su\,du}{a(u)} [\phi_m(u)]^n e^{-sa(u)R_{nm}}, \quad (24)$$

where

$$a(u) = (u^2 + 1/c_1^2)^{1/2}, \qquad b(u) = (u^2 + 1/c_2^2)^{1/2}$$

$$\phi_m(u) = \frac{\rho_2 a(u) - \rho_1 b(u)}{\rho_2 a(u) + \rho_1 b(u)},$$

and

$$R_{nm} = \begin{cases} 2nH + d - z, & m = 1 \\ 2nH - d - z, & m = 2 \\ 2nH - d + z, & m = 3 \\ 2nH + d + z, & m = 4. \end{cases} \quad \text{for}$$

In the above derivation we have assumed a Dirac $\delta(t)$-function for the excitation, whose Laplace transform is 1. Using now the change of variable (Spencer, 1956)

$$t = a(u)R_{nm}, \text{ and}$$

$$du = \frac{a(u)}{uR_{nm}}\, dt$$

equation (24) becomes

$$\bar{p}_e(0, z, s) = \sum_{n=1}^{\infty} \sum_{m=1}^{4} \frac{(-1)^{n+m-1}}{R_{nm}}\, s \int_{R_{nm}/c_1}^{\infty} [\Phi_m(t)]^n e^{-st} dt. \tag{25}$$

Note that the integral in equation (25) is simply the Laplace transform of the function

$$[\Phi_m(t)]^n H\left(t - \frac{R_{nm}}{c_1}\right).$$

$H(t)$ is the Heaviside unit function. We obtain immediately

$$p_e(0, z, t) = \sum_{n=1}^{\infty} \sum_{m=1}^{4} \frac{(-1)^{n+m-1}}{R_{nm}} \frac{d}{dt} \left\{ [\Phi_m(t)]^n H\left(t - \frac{R_{nm}}{c_1}\right) \right\}. \tag{26}$$

This is the axial response due to an excitation of an unit impulse $\delta(t)$. For the response of a time function $F(t)$, we can apply the convolution integral

$$P_e(0, z, t) = \int_{-\infty}^{\infty} p_e(0, z, t) F(t - \tau) d\tau.$$

Hence, we have

$$P_e(0, z, t) = \sum_{n=1}^{\infty} \sum_{m=1}^{4} \frac{(-1)^{n+m-1}}{R_{nm}} \left\{ K^n F\left(t - \frac{R_{nm}}{c_1}\right) + \int_{R_{nm}/c_1}^{t} F(t - \tau) \frac{d}{d\tau} [\Phi_m(\tau)]^n d\tau \right\} \tag{27}$$

where

$$K = \frac{\rho_2 c_2 - \rho_1 c_1}{\rho_2 c_2 + \rho_1 c_1}$$

is the plane wave reflection coefficient at normal incidence, and

$$\Phi_m(t) = \frac{t - \left(\frac{\rho_1}{\rho_2}\right)(t^2 - \zeta_{nm}^2)^{1/2}}{t + \left(\frac{\rho_1}{\rho_2}\right)(t^2 - \zeta_{nm}^2)^{1/2}}, \qquad \zeta_{nm}^2 = R_{nm}^2(c_1^{-2} - c_2^{-2}).$$

Adding formula (22) and equation (27), we finally obtain the axial transient pressure response

$$p_1(0, z, t) = \frac{1}{R} F\left(t - \frac{|z - d|}{c_1}\right) - \frac{1}{R'} F\left(t - \frac{z + d}{c_1}\right) + \sum_{n=1}^{\infty} \sum_{m=1}^{4} \frac{(-1)^{n+m-1}}{R_{nm}} \left\{ K^n F\left(t - \frac{R_{nm}}{c_1}\right) + \int_{R_{nm}/c_1}^{t} F(t - \tau) \frac{d}{d\tau} [\Phi_m(\tau)]^n d\tau \right\} . \tag{28}$$

In the above solution, we have assumed a liquid semi-infinite layer with density ρ_2 and velocity c_2 instead of the restriction of a rigid bottom.

The physical interpretation of the transient solution is not hard to grasp. The first two terms are simply the contribution due to the source and image. The first group of terms inside the summation ($m = 1, 2, 3, 4$) are multiples inside the water layer. These multiples not only decrease in amplitude by spherical divergence but also suffer a multiplying factor K^n where K is the reflection coefficient of a plane wave at normal incidence. The exponent n indicates the number of reflections from the bottom interface. The second group of terms ($m = 1, 2, 3, 4$) inside the summation are the "correction terms" (Spencer, 1956) for a spherical wave hitting an elastic plane boundary. These terms are the "tail" characteristic of two-dimensional wave propagation which is imposed on the initial spherical wave by the plane boundaries.

Calculation of the pressure response using equation (28) is laborious. However, an estimate can be made based on the axial response. For the purpose of illustration, we will choose a typical example, as follows:

$H = 150$ ft $\qquad z = 10$ ft

$K = 0.75$ $\qquad d = 5$ ft.

$c_1 = 5{,}000$ ft/sec

The choice of reflection coefficient of the value 0.75 is made in order to simulate a hard limestone bottom.

The amplitude versus time is plotted in Figure 3. This curve shows the envelope of the pressure amplitude as a function of time. From this curve it can be seen that the pressure amplitude decreases by 80 db in a time of about 1.2

seconds. However, in actual observation, the oscillatory traces often last much longer than the predicted time. It should be pointed out that the assumed reflection coefficient of 0.75 appears to be very high for most offshore areas. For smaller values, the decay time would be still shorter.

Therefore, we may conclude that in actual practice the observed oscillatory

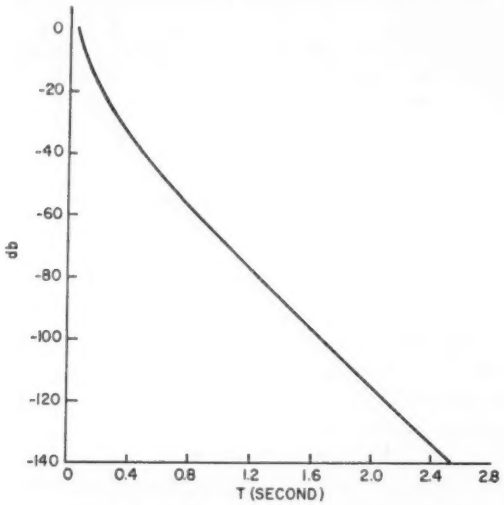

FIG. 3. Transient pressure amplitude versus time ($H=150$ ft, $K=0.75$).

phenomenon in offshore seismic exploration cannot be fully explained in terms of the assumed model.

In 1955, California Research Corporation conducted controlled experiments on the observed offshore oscillatory phenomenon which further sustained the above conclusion. Werth, Liu, and Trorey (1959) have put forth an alternative explanation that the "singing" phenomenon could be caused by the reflected energy from a deeper horizon.

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GEOPHYSICS, VOL. XXIV, NO. 4 (OCTOBER, 1959), PP. 667–680, 8 FIGS.

A LOSS MECHANISM FOR THE PIERRE SHALE*

C. W. HORTON†

ABSTRACT

A theoretical study is made of a fairly simple model of an elastic solid in which losses are attributed to both the shear modulus and the bulk modulus. Each of these elastic parameters is represented by a circuit containing two springs and one dashpot. This is a modification of the usual Kelvin solid that has finite stiffness at infinite frequency. The four relaxation times introduced in the model are determined to fit the experimental data presented by McDonal *et al.* (1958). It is shown that one can obtain a very good representation of their experimental data with the model described above. The wave equation for an elastic solid is given in a canonical form so that one can compare easily the behavior of different models of the elastic parameters.

INTRODUCTION

There are two successful approaches to the representation of the loss mechanisms of a solid. One approach is to assume one or more relaxation times τ for the medium. Since a relaxation process produces a frequency dependent loss that has its maximum effect near the angular frequency $1/\tau$, experimentally determined losses can be "explained" over an arbitrarily large frequency band by introducing a suitable distribution of the relaxation times over the same frequency bands. In the limit one has the entire spectrum of relaxation times $0 \leq \tau < \infty$; a case which has been discussed thoroughly by Gross (1953).

The second approach involves the use of equivalent circuits in which the elastic compliance is represented by a capacitance and losses are represented by resistances, or conversely. Experimental loss functions over a given frequency range can be approximated arbitrarily closely by using a sufficient number of resistances and capacitances in the equivalent circuit. It is easily seen that this method is closely related to the one described above since an *RC*-network has one relaxation time associated with it while $(N+1)$ resistances and $(N+1)$ capacitances arranged in one of the canonical forms described by Roscoe (1950) has N relaxation times. Thus in the limit as the network contains an infinite number of meshes, it becomes equivalent to an infinite set of relaxation times. The equations relating these limiting cases are analyzed by Gross (1953). The reader is also referred to Richardson (1957) for a general discussion and to Roscoe (1950) for a particular discussion of the equivalent circuits used to represent loss mechanisms. A recent paper by Knopoff and MacDonald (1958) contains an excellent discussion of the problem.

In the practical problem one usually knows the attenuation over a limited frequency range and one prefers to introduce the simplest equivalent circuit or the fewest relaxation times that are necessary to explain the data. An example of

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this approach is the use of the Kelvin solid as a model for the earth. As soon as it became apparent that the attenuation of seismic waves in the earth increased with frequency, one loss element was introduced in the equivalent circuit for

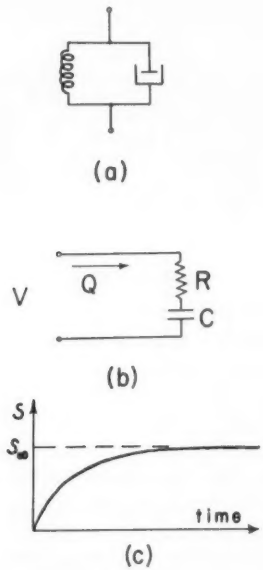

FIG. 1. (a) The representation of a Kelvin solid with a spring and dashpot. (b) The equivalent electric circuit for a Kelvin solid. (c) The response of the circuit (a) to a Heaviside step function. s is the strain.

the shear modulus. This led to the well-known Kelvin solid which is illustrated in Figure 1a as a spring and dashpot in parallel. The resulting response function for a Heaviside step function input is shown in Figure 1c. In the usual Kelvin model it is assumed that the bulk modulus is free of losses.

If one introduces electric analogies in accordance with the scheme shown in Table I, one obtains the electrical circuit shown in Figure 1b as the electrical

TABLE I

ELECTRIC EQUIVALENTS USED IN THE DISCUSSION

Elastic property	Electric Analog
stress	voltage
dilatation	charge
losses (dashpot)	resistance
modulus	1/capacitance
mass	inductance

equivalent of the Kelvin solid. The capacitance C represents the elastic compliance while the resistance R represents the dashpot. The relaxation time $(RC)^{-1}$ of the electrical circuit is equal to the relaxation time of the mechanical solid. The fact that the electrical circuit is in series while the mechanical circuit is in parallel is a result of the use of the equivalence between stress and voltage. Roscoe (1950) shows that one can avoid this feature by introducing electrical circuits in which current is the analog of stress. In this case one obtains an electrical network which is the dual of Figure 1b. This same dichotomy occurs in the use of equivalent circuits to represent lumped mechanical systems such as geophones.

It seems to the writer to be much more natural to use voltage rather than electric current as the analog of pressure and this will be done. However, Roscoe (1950) points out the use of electric current for the analog of pressure is advantageous in applying Kirchhoff's laws for networks.

THE KELVIN SOLID

Theoretical studies of the propagation of seismic waves in a Kelvin solid have been made by a large number of authors, but only one reference will be cited. This is the paper by Ricker (1943) in which he gives curves of the attenuation and phase velocity of a periodic wave versus the frequency of the wave. There are two basic features of the behavior of a Kelvin solid that make it unsatisfactory as a representation of the earth. The first of these is the dependence of attenuation on frequency. Ricker's study (1943), shows that if the attenuation of a periodic plane wave is represented by $\exp(-kx)$, the parameter k is proportional to the square of the frequency for a Kelvin solid. At that time experimental evidence was not clear, but since then two papers (Collins and Lee, 1956 and McDonal *et al.*, 1958) have presented very strong evidence that the parameter k depends more nearly on the first power of the frequency.

The second way in which the Kelvin solid fails is that the phase velocity of a periodic wave becomes infinite as the frequency of the wave becomes infinite. It may be argued that this is not a fair criticism since the model is valid only at low frequencies. Even so, this difficulty means that the model is not very satisfactory to use in analyzing the propagation of pulses. If the pulse has a finite time duration, it will have an infinite frequency spectrum. According to the prediction of the theory, these infinite frequencies are propagated infinitely fast and, as Jeffreys (1931) pointed out, there is a "displacement at any instant, however early." The problem of the propagation in a Kelvin solid of a disturbance whose initial shape is a Dirac-delta function has been analyzed very thoroughly by Hanin (1957). Hanin obtains solutions which are suitable for easy numerical computation for the forerunner, the main pulse shape, and the tail. He, too, concludes "the presence of the disturbances is felt immediately everywhere in the medium."

Another aspect of the behavior of the Kelvin solid at high frequencies is the

response to a Heaviside step function. As shown in Figure 1c, when the stress is suddenly applied, the immediate result is zero displacement, i.e., infinite rigidity. This violation of one's intuitive feelings can be "explained away" as the result of applying the model in a frequency range to which it does not apply.

A MODIFICATION OF THE KELVIN SOLID

It has been argued above that the Kelvin solid is not satisfactory as a representation of the elastic properties of the earth. An application of William of Occam's razor shows us that we should not add any more complications to the

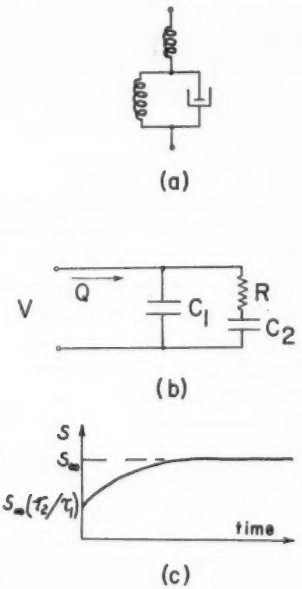

FIG. 2. (a) The representation of a modified Kelvin solid with two springs and one dashpot. (b) The equivalent electric circuit for the modified Kelvin solid. (c) The response of the circuit (a) to a Heaviside step function. s is the strain.

theory than are necessary to explain the experimental data at hand. The next most simple model is that shown in Figures 2a and 2b in which one additional compliance, or equivalently, one additional relaxation time is added. This model eliminates two of the difficulties listed above. In the first place the phase velocity at infinite frequencies remains finite. Secondly, the immediate response to a Heaviside step function is a non-zero fraction of the final response as shown in Figure 2c. The analysis given below shows that the dependence of attenuation on frequency does not show the linearity required by the experimental data and

so one is forced to introduce a more elaborate model, i.e., introduce similar losses in the bulk modulus.

The model illustrated in Figure 2a has been analyzed by Hillier (1949) in a study of the propagation of longitudinal waves in high polymer filaments. The losses were attributed to only one elastic modulus. The analysis of this model for one elastic modulus is summarized by Kolsky (1953, pp. 118–121). Geuze and Tjong-Kie (1954) describe experiments on the shear modulus of hollow tubes of pottery clay at a water content of 48 percent dry weight. When a sudden torque was applied, the resulting shear showed a curve much like that of Figure 2c, but the time scale was much larger than that discussed below.

The seismic literature does not contain many references to the possibilities of losses associated with bulk modulus, yet a particulate medium such as clay or sand is ideally suited for this kind of loss. The hydrostatic stress could be supported initially by a framework within the medium, but after a short time interval a readjustment of this framework would transfer the stress to other parts of the medium with a subsequent change in the dilatation. Alternate mechanisms of volume losses involving chemical reactions in the fluids may be involved. Liebermann (1949) has shown the significance of this kind of process for the attenuation of sound waves in the ocean.

In the latter part of this paper it is shown that the experimental measurements of McDonal *et al.* (1958) on the attenuation of shear and compressional waves in the Pierre Shale of Colorado, can be explained satisfactorily by introducing two relaxation times in the shear modulus and two relaxation times in the bulk modulus.

RELAXATION TIMES OF THE ELASTIC MODEL

The equation for the electrical circuit shown in Figure 2b is

$$V + \tau_2 \dot{V} = k[Q + \tau_1 Q] \tag{1}$$

where

$$\tau_1 = RC_2 \tag{2}$$

$$\tau_2 = RC_2[1 + (C_2/C_1)]^{-1} \tag{3}$$

or

$$\tau_1/\tau_2 = 1 + (C_2/C_1) \qquad (\geq 1) \tag{4}$$

and

$$k = 1/(C_1 + C_2). \tag{5}$$

If this model be applied to the bulk modulus k, one can use the equivalences given in Table I to replace V by p, and Q by θ to obtain

$$p + \tau_2 \dot{p} = k[\theta + \tau_1 \dot{\theta}]. \tag{6}$$

If the stresses and strains have a time periodicity exp $(-i\omega t)$, this equation leads to the following complex bulk modulus

$$k = k^{(0)}f(\omega) = k^{(0)}(1 - i\omega\tau_1)/(1 - i\omega\tau_2). \tag{7}$$

Thus one has a complex bulk modulus k which has the real value $k^{(0)}$ at zero frequency and the real value $k^{(h)}=(\tau_1/\tau_2)k^{(0)}$ at very high frequencies. It is evident from equation (4) that $\tau_1/\tau_2 \geq 1$.

It will be assumed that the shear modulus can be represented by the circuit in Figure 2a with different values for the parameters. Hence, one may write, for periodic stresses and strains,

$$P_{ij} = 2\mu E_{ij} = 2\mu^{(0)}g(\omega)E_{ij} \tag{8}$$

where

$$g(\omega) = (1 - i\omega\tau_3)/(1 - i\omega\tau_4). \tag{9}$$

Here $\mu^{(0)}$ is the shear modulus at zero frequency, and P_{ij} and E_{ij} are the deviatoric stress and strain tensors, respectively. The value of the shear modulus at very high frequencies is $\mu^{(h)}=(\tau_3/\tau_4)\mu^{(0)}$ where $(\tau_3/\tau_4)\geq 1$.

A CANONICAL FORM OF THE WAVE EQUATION

All of the essential features of attenuation can be illustrated by considering a plane wave exp $(i\alpha x - i\omega t)$ where $\alpha=\alpha(\omega)=\alpha_2+i\alpha_1$. The real part, α_2, is called the phase function and is related to the phase velocity by $\alpha_2=\omega/V_{ph}$. The imaginary part, α_1, is called the attenuation and is actually the attenuation in nepers per unit distance.

No matter what form of loss mechanism is postulated, each elastic modulus μ and k, can be described by a complex value for a given frequency, as done above in equations (7) and (8). When these complex values are substituted into the wave equation for a plane longitudinal wave, one obtains

$$V_P^{(0)2}[A(\omega) - iB(\omega)]\alpha^2 = \omega^2. \tag{10}$$

Similarly the wave equation for a plane rotational wave is

$$V_S^{(0)2}[A(\omega)^* - iB(\omega)^*]\alpha^{*2} = \omega^2. \tag{11}$$

The asterisk is used to indicate that the corresponding quantity refers to the rotational wave and not to denote complex conjugate.

The definitions of the functions $A(\omega)$, $B(\omega)$, etc., are given in Table II for various models of the loss mechanisms. It will be noted that the following generalization holds in each case except that of rotational waves in a Maxwell liquid. As $\omega\to 0$, $A(\omega)\to 1$ and $B(\omega)\to 0$. Thus $V_P^{(0)}$ and $V_S^{(0)}$ are the phase velocities of waves with vanishing frequency. As ω increases, $A(\omega)$ increases monotonically from unity and slowly approaches a limit as $\omega\to\infty$. This limit is finite in every case except the Kelvin solid. On the other hand, in every case except the Kelvin

TABLE II. PARAMETERS OF THE CANONICAL WAVE EQUATION FOR VARIOUS ELASTIC MODELS

a. $F(x) = x^2/(1+x^2)$

b. $G(x) = x/(1+x^2)$

c. $V_p^{(0)} = \left[k^{(0)} + \frac{4}{3}\mu^{(0)}\right] \Big/ \rho$

d. $V_s^{(0)^2} = \mu^{(0)}/\rho$

e. For Maxwell liquid

$V_p^{(0)^2} = k^{(0)}/\rho$

$V_s^{(0)} = 0$

f. $P = \left[1 - \frac{4}{3}\left(\frac{V_s^{(0)}}{V_p^{(0)}}\right)^2\right]\frac{\tau_1 - \tau_2}{\tau_2}$

MODEL	IDEAL		KELVIN SOLID		MAXWELL LIQUID		MODIFIED KELVIN		PRESENT MODEL	
MODULUS	k	μ	k	μ	k	μ	k	μ	k	μ
MECHANICAL DIAGRAM Springs & dashpots										
ELECTRIC DIAGRAM										
RESPONSE TO HEAVISIDE STRESS										
DEVIATORIC EQ.	$P_{ij} = 2\mu E_{ij}$		$P_{ij} = 2\mu\left[E_{ij} + \tau_3 \frac{dE_{ij}}{dt}\right]$		$2\mu_M \frac{dE_{ij}}{dt} = \frac{dP_{ij}}{dt} + \frac{1}{\tau_3} P_{ij}$		$P_{ij} + \tau_4 \frac{dP_{ij}}{dt} = 2\mu\left[E_{ij} + \tau_3 \frac{dE_{ij}}{dt}\right]$		$P_{ij} + \tau_4 \frac{dP_{ij}}{dt} = 2\mu\left[E_{ij} + \tau_3 \frac{dE_{ij}}{dt}\right]$	
$k(\omega)$ and $\mu(\omega)$ for $\exp(-i\omega t)$	$k^{(0)}$	$\mu^{(0)}$	$k^{(0)}$	$\mu^{(0)}(1-i\omega\tau_3)$	$k^{(0)}$	$\mu_M\left\{\frac{-i\omega\tau_3}{1-i\omega\tau_3}\right\}$	$k^{(0)}$	$\mu^{(0)}\left\{\frac{1-i\omega\tau_3}{1-i\omega\tau_4}\right\}$	$k^{(0)}\left\{\frac{1-i\omega\tau_1}{1-i\omega\tau_2}\right\}$	$\mu^{(0)}\left\{\frac{1-i\omega\tau_3}{1-i\omega\tau_4}\right\}$
$k^{(\infty)}$ and $\mu^{(\infty)}$ i.e., lim as $\omega \to \infty$	$k^{(0)}$	$\mu^{(0)}$	$k^{(0)}$	$-i\infty$	$k^{(0)}$	μ_M	$k^{(0)}$	$(\tau_3/\tau_4)\mu^{(0)}$	$(\tau_1/\tau_2)k^{(0)}$	$(\tau_3/\tau_4)\mu^{(0)}$
$A(\omega)$ see note a	1		1		$1 + P' F(\omega\tau_3)$		$1 + P' F(\omega\tau_4)$		$1 + P F(\omega\tau_2) + P' F(\omega\tau_4)$ see note f	
$B(\omega)$ see note b	0		$P'\omega\tau_3$		$P' G(\omega\tau_3)$		$P' G(\omega\tau_4)$		$P G(\omega\tau_2) + P' G(\omega\tau_4)$ see note f	
P'	—		$\frac{4}{3}\left[\frac{V_s^{(0)}}{V_p^{(0)}}\right]^2$		$\frac{4}{3}\frac{\mu_M}{k^{(0)}}$ see note e		$\frac{4}{3}\left[\frac{V_s^{(0)}}{V_p^{(0)}}\right]^2 \frac{\tau_3 - \tau_4}{\tau_4}$		$\frac{4}{3}\left[\frac{V_s^{(0)}}{V_p^{(0)}}\right]^2 \frac{\tau_3 - \tau_4}{\tau_4}$	
$V_p^{(\infty)}$ see note c	$V_p^{(0)}$		∞		$V_p^{(0)}\sqrt{1+P'}$ see note e		$V_p^{(0)}\sqrt{1+P'}$		$V_p^{(0)}\sqrt{1+P+P'}$	
$A(\omega)^*$	1		1		$F(\omega\tau_3)$		$1 + Q F(\omega\tau_4)$		$1 + Q F(\omega\tau_4)$	
$B(\omega)^*$	0		$\omega\tau_3$		$G(\omega\tau_3)$		$Q G(\omega\tau_4)$		$Q G(\omega\tau_4)$	
Q	—		—		—		$(\tau_3 - \tau_4)/\tau_4$		$(\tau_3 - \tau_4)/\tau_4$	
$V_s^{(\infty)}$ see note d	$V_s^{(0)}$		•		$[\mu_M/\rho]^{1/2}$ see note e		$V_s^{(0)}\sqrt{1+Q}$		$V_s^{(0)}\sqrt{1+Q}$	

solid $B(\omega)$ approaches zero as $\omega \to 0$ or ∞ and has one or more maxima, depending on the number of relaxation times. In the cases of geophysical interest that have been encountered so far $B(\omega) \ll 1$ so that the ratio B/A is much less than unity at all frequencies.

In view of the identity in form of equations (10) and (11) it is sufficient to discuss the solution of the former. Stratton (1941) shows that the solution is

$$\alpha_1 = \frac{\omega}{V_P{}^{(0)}} \left[\frac{1}{2A} \frac{1}{1+x} \left\{ \sqrt{1+x} - 1 \right\} \right]^{1/2} \tag{12}$$

$$\alpha_2 = \frac{\omega}{V_P{}^{(0)}} \left[\frac{1}{2A} \frac{1}{1+x} \left\{ \sqrt{1+x} + 1 \right\} \right]^{1/2} \tag{13}$$

where

$$x = (B/A)^2. \tag{14}$$

For purposes of plotting it is better to use the following dimensionless forms (with $\omega\tau_4$ as the abscissa)

$$\alpha_1 V_P{}^{(0)} \tau_4 = \omega\tau_4 \sqrt{f_1(x)/4A} \tag{15}$$

$$V_{\text{phase}}/V_P{}^{(0)} = \omega/\alpha_2 V_P{}^{(0)} = \sqrt{A f_2(x)} \tag{16}$$

where

$$f_1(x) = \frac{2}{1+x} \left[\sqrt{1+x} - 1 \right] \tag{17}$$

$$f_2(x) = 2(1+x)\left[\sqrt{1+x} + 1 \right]^{-1}. \tag{18}$$

Figures 3 and 4 show plots of $f_1(x)$ and $f_2(x)$ over a wide range of x. It is seen that $f_1(x) = x$ and $f_2(x) = 1$ for $(B/A)^2 < 0.01$ or $(B/A) < 0.1$.

THE EXPERIMENTAL ATTENUATION DATA FOR THE PIERRE SHALE

The recent article by McDonal (1958) gives the attenuation of rotational waves in the Pierre Shale of Colorado over the frequency range 25 to 125 cps. The last column of Table II shows that the propagation of shear waves is governed by equation (11) with

$$A(\omega)^* = 1 + QF(\omega\tau_4) \tag{19}$$

$$B(\omega)^* = QG(\omega\tau_4) \tag{20}$$

$$Q = (\tau_3 - \tau_4)/\tau_4. \tag{21}$$

The functions F and G are defined by

$$F(x) = x^2/(1+x^2), \quad \text{and} \quad G(x) = x/(1+x^2).$$

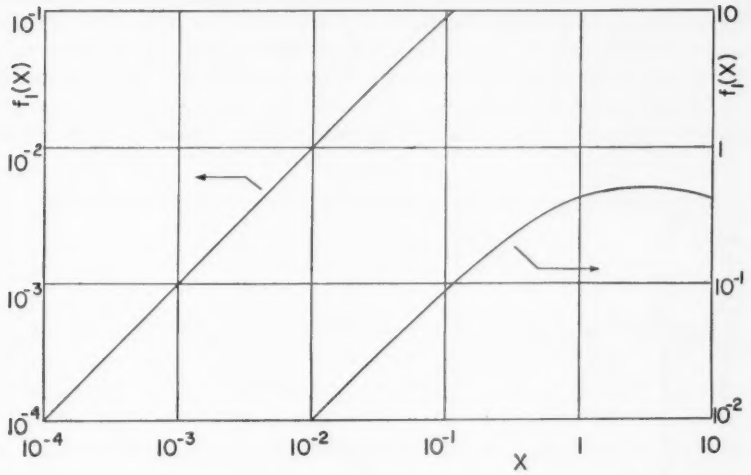

FIG. 3. A plot of $f_1(x)$ versus x.

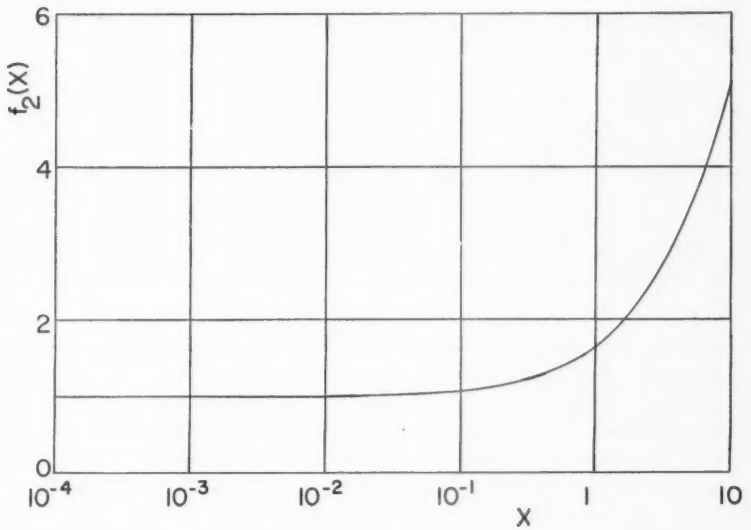

FIG. 4. A plot of $f_2(x)$ versus x.

The choice of τ_4 determines the frequency band over which the attenuation α_1^* is approximately linear while the choice of Q determines the slope of the attenuation curve versus frequency. Once τ_4 and Q are determined, one can compute τ_3. By trial and error the following constants have been found to give the best fit. $Q=0.25$, $\tau_4=1.45$ milliseconds, and, consequently, $\tau_3=1.81$ milliseconds. The quality of the fit is shown in Figure 5 in which α_1^* is compared with the experi-

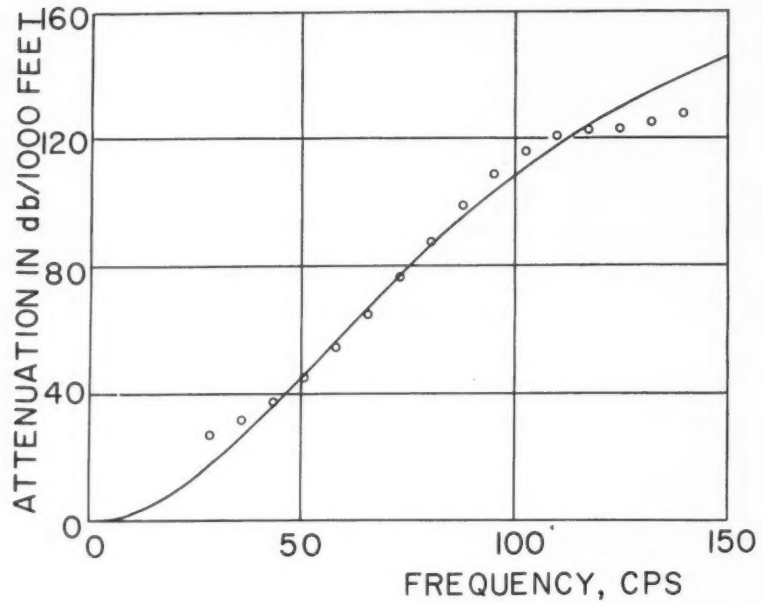

FIG. 5. The attenuation α_1^* of transverse waves versus frequency. The solid curve is theory; the circles are McDonal's (1958) experimental data.

mental data of McDonal *et al.* (1958, Figure 12). The effect of the parameters is fairly sensitive since a change of 5 percent in the values of Q or τ_4 will give noticeably poorer agreement between the experimental data and the theoretical curve.

Now that two of the relaxation times have been determined from the attenuation of the rotational waves, one can use the attenuation of the longitudinal waves to determine the other relaxation times. The last column of Table II shows that for longitudinal waves

$$A(\omega) = 1 + PF(\omega\tau_2) + P'F(\omega\tau_4) \tag{22}$$

$$B(\omega) = PG(\omega\tau_2) + P'G(\omega\tau_4) \tag{23}$$

where

$$P = \frac{k^{(0)}}{\mu^{(0)}}\left[\frac{V_S{}^{(0)}}{V_P{}^{(0)}}\right]^2 \frac{\tau_1 - \tau_2}{\tau_2} \tag{24}$$

$$= \left\{1 - \frac{4}{3}\left[\frac{V_S{}^{(0)}}{V_P{}^{(0)}}\right]^2\right\}\frac{\tau_1 - \tau_2}{\tau_2}$$

and

$$P' = \frac{4}{3}\left[\frac{V_S{}^{(0)}}{V_P{}^{(0)}}\right]^2 \frac{\tau_3 - \tau_4}{\tau_4}. \tag{25}$$

The constant P' is determined uniquely from the values of $V_P{}^{(0)}$ and $V_S{}^{(0)}$ and the relaxation times τ_3 and τ_4. The values $V_P{}^{(0)} = 7{,}100$ ft/sec and $V_S{}^{(0)} = 2{,}680$ ft/sec found by McDonal and the values of τ_3 and τ_4 given above yield $P' = 0.047$. By trial and error computation the values $P = 0.065$ and $\tau_2 = 0.145$ milliseconds were found. These values lead in turn to a value of $\tau_1 = 0.157$ milliseconds.

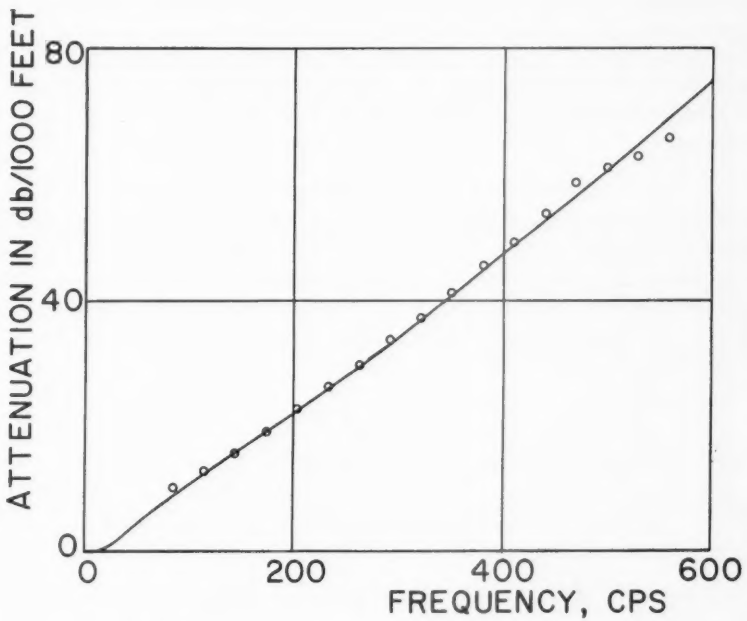

FIG. 6. The attenuation α_1 of longitudinal waves versus frequency. The solid curve is theory; the circles are McDonal's (1958) experimental data.

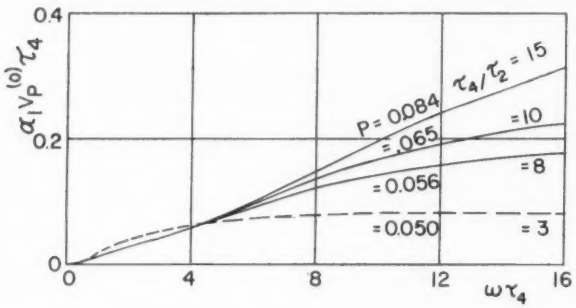

FIG. 7. Curves to show the effect of the ratio τ_4/τ_2 on the attenuation α_1 of longitudinal waves. In each case $P'=0.047$. P is chosen so that the values of α_1 are the same at $\omega\tau_4=4$.

The extent of the agreement between the experimental values and the theoretical calculations is shown in Figure 6.

The function $A(\omega)$ defined in equation (22) may have two separate maxima at $\omega=1/\tau_2$ and $1/\tau_4$. The ratio τ_4/τ_2 determines the separation of these maxima and the frequency range over which the attenuation α_1 approximates a linear function of frequency. The effect of changes in the ratio τ_4/τ_2 is shown in Figure 7. In these curves the value P' was held fixed but P was varied so that α_1 had the same value for $\omega\tau_4=4$. The larger the ratio τ_4/τ_2 the larger the frequency range over which α_1 approximates a linear frequency dependence but the greater the oscillations.

THE DEPENDENCE OF PHASE VELOCITY ON FREQUENCY

The phase velocity of rotational and longitudinal waves can be computed as a function of frequency from the formulas given in Table II. Although there are no experimental data with which to compare the results, it is of interest to determine the amount of variation required by the attenuation data. Figure 8 shows

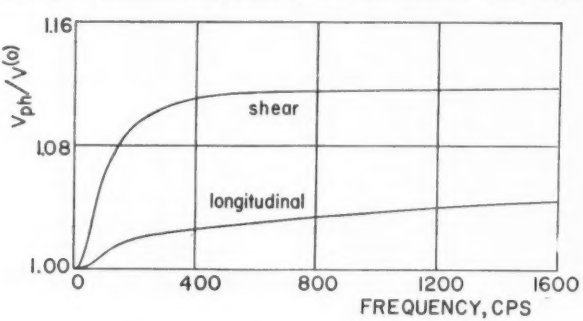

FIG. 8. The dependence of the phase velocities on the frequency.

graphs of $V_S/V_S^{(0)}$ and $V_P/V_P^{(0)}$ versus frequency in cps based on the parameters and relaxation times given above. The variation of the phase velocity of the longitudinal waves is only 5.5 percent. The rotational wave shows a variation of 12 percent, most of which is concentrated in the critical frequency range of 25 to 400 cps. Measurements of velocities in the kilocycle region will offer an interesting extension of the analysis given in this paper.

SUMMARY

The analysis given in this paper offers good evidence that volume viscosity plays a significant role in the attenuation of longitudinal waves in the Pierre Shale. Presumably this type of loss occurs in all clastic formations. The loss mechanisms introduced in this paper provided four relaxation time constants that can be adjusted to fit the observed attenuation data. These relaxation times can be chosen so that the theoretical curves agree quite well with the experimental data. The only question left is: How reliable are the theoretical curves outside the frequency range of the experimental data? The answer is that one has no guarantee of the number and kinds of relaxation processes that occur until measurements are carried out over an extended frequency range.

When the experimental data are extended to higher and lower frequencies, the new data can undoubtedly be fitted by adding more elements to the canonical circuits representing the loss mechanisms. The virtue of using the canonical form of the network is that each resonant circuit acts more or less independently of the others so that the relaxation times found in this paper will be subject to only minor changes in the fitting of the extended frequency data.

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GEOPHYSICS, VOL. XXIV, NO. 4 (OCTOBER, 1959), PP. 681–691, 3 FIGS.

SEISMIC RECIPROCITY*

LEON KNOPOFF† AND ANTHONY F. GANGI†

ABSTRACT

The reciprocity relationship describing the relations among the fields resulting from the interchange of point sources and receivers may be extended to the seismic case. Seismic reciprocity can be described either in terms of the scalar product of the vectors representing the excitation of the source and the field at the receiver, or in terms of a Green's tensor describing these two quantities. Theoretical reciprocity relations give no information concerning reciprocity in the cases for which the scalar product vanishes. A simple experiment in the vector case demonstrates that reciprocity is not obtained when the scalar product of the two vectors vanishes.

INTRODUCTION

Reciprocity relations are found in many disciplines of physics. These usually describe relationships among potentials satisfying either Laplace's equation or the ordinary wave equation. These reciprocity relations usually state that, if for fixed geometry of obstacles and other bodies in the vicinity of sources and receivers, a source is placed at some point P and the potentials are observed at some point Q, then the same potentials will be observed at P if the source is placed at Q.

These relations are usually derived on the basis of Green's theorem for a particular kind of potential function. Familiar examples are Green's reciprocity theorem for scalar potentials satisfying Laplace's equation (Smythe, 1950, p. 34–54), the Helmholtz reciprocal relationship for harmonic scalar potentials satisfying the wave equation (Rayleigh, 1945, p. 145) and the Lorentz symmetry relation for electromagnetic waves from two sources (Stratton, 1941, p. 479).

In all the above cases the reciprocity relations are applicable only to scalar problems. Consider, for example, the case of an electrostatic point charge at a point P in the vicinity of an infinite conducting sheet. The potential at Q is the same as that at P were the charge at Q. However the electric fields in the two cases are not the same. The reason for this is obvious; it is the electric potential which satisfied Laplace's equation and not the electric field. In turn, Green's theorem for this case depends upon the application of Laplace's equation.

Reciprocity relations have also been given for vector fields. Examples are to be found for the cases of the electromagnetic field (Bateman, 1944, p. 201), static elasticity (Love, 1944, p. 173) and also for more general vector fields (Courant and Hilbert, 1953, p. 394; Morse and Feshbach, 1953, p. 882).

It is the purpose of this paper to review the mathematical theorems of reciprocity and apply them to the problems of seismic theory.

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RECIPROCITY RELATIONS

The usual derivation of vector reciprocity depends upon the demonstration that the differential equations describing the field are self-adjoint. If the differential equations be written as

$$\mathfrak{L}_{ij}(u_i) = f_i \tag{1}$$

where u is the dependent variable, $\mathfrak{L}$ is a linear self-adjoint operator and f is the inhomogeneous term, then it is not difficult to show, under the assumption of homogeneous boundary conditions, that

$$u_i(P, Q)f_i(P) = u_i(Q, P)f_i(Q) \tag{2}$$

where $u(P, Q)$ represents the value of u at P due to a point source of $f(Q)$ at Q. In Appendix I, the derivation of equation (2) is carried out. Introducing the Green's tensor G_{ij},

$$u_i(P, Q) = G_{ij}(P, Q)f_j(Q) \tag{3}$$

and substituting into equation (2) , we have

$$G_{ij}(P, Q) = G_{ji}(Q, P). \tag{4}$$

This statement of the reciprocity relation is equivalent to that of equation (2).

We consider the case of the elastic wave equation,

$$\tau_{ij,j}(R, P) - \rho(R)u_{i,tt}(R, P) = f_i(P), \tag{5}$$

where τ is the stress tensor, u is the displacement of a particle, f is the body force vector per unit volume and ρ is the density. Indices following commas indicate differentiation with respect to these coordinates. The stress tensor may be written in terms of the displacement as

$$\tau_{ij}(R, P) = C_{ij}^{kl}(R)\{u_{k,l}(R, P) + u_{l,k}(R, P)\} \tag{6}$$

where the tensor quantities C are the elastic moduli. If we assume the forces at P and Q to have the same time dependence, then a linear time transform of (5) can be written as

$$\tau_{ij,j} - \rho s^2 \bar{u}_i = \bar{f}_i \tag{7}$$

where the barred quantities are the transforms of the corresponding unbarred quantities. Because of the symmetry among the components of C, even in the most anisotropic case (Sokolnikoff, 1956, p. 63),

$$C_{ij}^{kl} = C_{ij}^{lk} = C_{ji}^{kl} = C_{ji}^{lk} = C_{kl}^{ij} = C_{kl}^{ji} = C_{lk}^{ij} = C_{lk}^{ji} \tag{8}$$

equation (2) can be shown to be satisfied. Hence the reciprocity relations (2) and (4) hold for elastodynamics for a medium having arbitrary inhomogeneity and anisotropy, if the time dependences of $f(P)$ and $f(Q)$ are identical.

EXAMPLES OF SEISMIC RECIPROCITY

The great advantage of reciprocity theorems is their generality. The theorem given above applies to an elastic medium having arbitrary boundaries, arbitrary inhomogeneity, and arbitrary anisotropy. A few examples will illustrate the conditions under which reciprocity holds.

Case I.

Let a point source of force be applied at P, directed in the x-direction and let the x-component of the motion be measured at Q. If an identical point source of force is applied at Q also directed along x, then the x-component of motion at P is identical to that measured at Q in the first case. Stated mathematically,

$$G_{xx}(P, Q) = G_{xx}(Q, P)$$

or

$$u_x(P, Q)f_x(P) = u_x(Q, P)f_x(Q).$$

A simple laboratory experiment has been performed to demonstrate reciprocity in this case. Consider the problem of an elastic half-space upon which a source transducer is placed exerting a normal force and upon which a receiver is placed so that the normal component of motion is detected. An obstacle is placed on the path between the two transducers. Elementary considerations will show that the interchange of source and receiver is equivalent to keeping the source and receiver fixed and moving the obstacle to the image point.

Upon the polished plane surface of a large granite block, two identical lithium sulfate transducers were placed 13.5 cm apart; one transducer acted as source, the other acted as receiver. The circuitry was that of standard modeling practice used to excite stress pulses of short duration in solids. A normal stress was obtained at the source; the normal component of the motion was observed at the detector. A 2.5 cm diameter by 2.5 cm high cylindrical brass block was placed on the line between the two transducers and coupled to the granite surface through a thin film of lubricant. The lubricant coupling is present for ease in moving the obstacle. The lubricant prevents shear stresses and tangential motions from being transmitted across the boundary between the granite and the brass. The reciprocity theorem should hold for any obstacle independent of the method of its coupling.

Figure 1 shows the photographic record obtained for the motion at the receiver for a number of positions of the brass obstacle on the path between the two transducers. The traces at the top and bottom of the record are 250 kc sine wave signals used to calibrate the time base of the remaining traces. The second trace of the record is the motion without the obstacle and the remaining traces are the total motion, including the scattered motion at the receiver, as a function of the position of the cylinder. The coordinates indicated are the distances of the center of the obstacle from the midpoint between the two transducers; the obstacle was moved in one-half cm steps from receiver to transmitter.

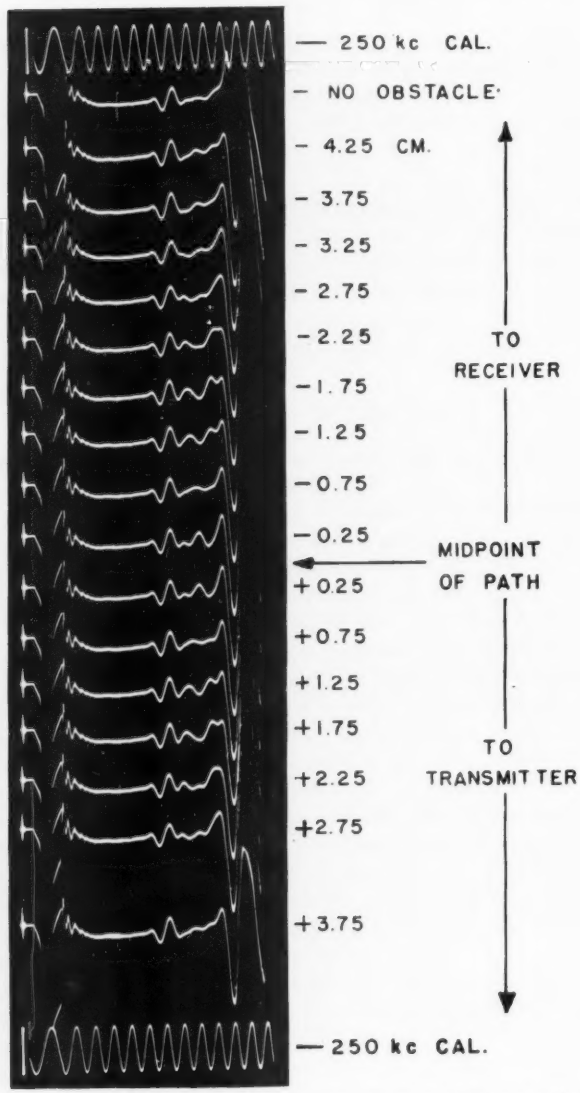


FIG. 1. Scattering from a brass obstacle between vertically directed lithium sulfate transducers, located on the plane surface of a large homogeneous granite block.

The complex pattern at the left of each record is a time mark to indicate the time at which the pulse originated at the source transducer. At about the center of each trace, the first event appears, identifiable as a compression (P) wave from the source. The large signal at the extreme right of the trace, extending off the oscilloscope screen is the Rayleigh (R) wave. The quiet trace between the events P and R in the case of the motion without the obstacle, testifies to the quality of the excitation of the model by a stress pulse of short duration with negligible reverberation following the initial pulse. Some of the scattered motions in the presence of the obstacle are found between the P and R events. The reciprocity in the records between obstacle positions having the same positive and negative coordinates can be seen.

The significant events in Lamb's problem without any obstacle are the P and R events; this is evident both from theory (Lamb, 1904) and from the first trace of the motion in Figure 1. A weak S arrival is predicted but we concern ourselves in this discussion with the two prominent arrivals, P and R. If the obstacle acts as a virtual source then each of the two incident waves should excite the obstacle again as a virtual source of both P and R. Thus the scattered waves PP, PR, RP and RR should be observed, where the first symbol refers to the incident wave and the second to the emergent wave. The events PP and RR arrive at the same time as the direct waves P and R from the source respectively. From Figure 1, the amount of PP scattering is small. The oscillatory record between the P and R events are the RP and PR scattered motions. Since the velocity of P waves is greater than that of R waves, it is evident that for stations closer to the receiver than the transmitter, the PR event precedes the RP event while at the corresponding stations closer to the transmitter, the order of these events in time is interchanged. A direct investigation of Figure 1 shows that the RP scattering at an obstacle location is the same as the PR scattering at the image location. This is a direct consequence of the reciprocity theorem of equation (4).

A second experiment, similar to the above, shows reciprocity again but shows the RP and PR wavelets more clearly. Upon the edge of a large sheet of aluminum, 1.82 mm thick, source and receiving barium titanite transducers were normally directed as before. The transducer spacing in this case was 50 cm. A cylindrical brass obstacle 0.35 cm diameter by 1.25 cm high was moved in four cm steps along the edge from source to receiver as before. The RP-PR reciprocity is again clearly observed in the record of Figure 2. Because of the increased transducer spacing the PR and RP events are clearly separated. Reverberation in the obstacle can be identified in terms of the extended "tail" of the RP and PR events.

Case II

In a second example let a point source of force be applied at P directed in the x-direction and let the y-component of the motion be measured at Q, x at right angles to y. If an identical point source of force be applied at Q directed along y,

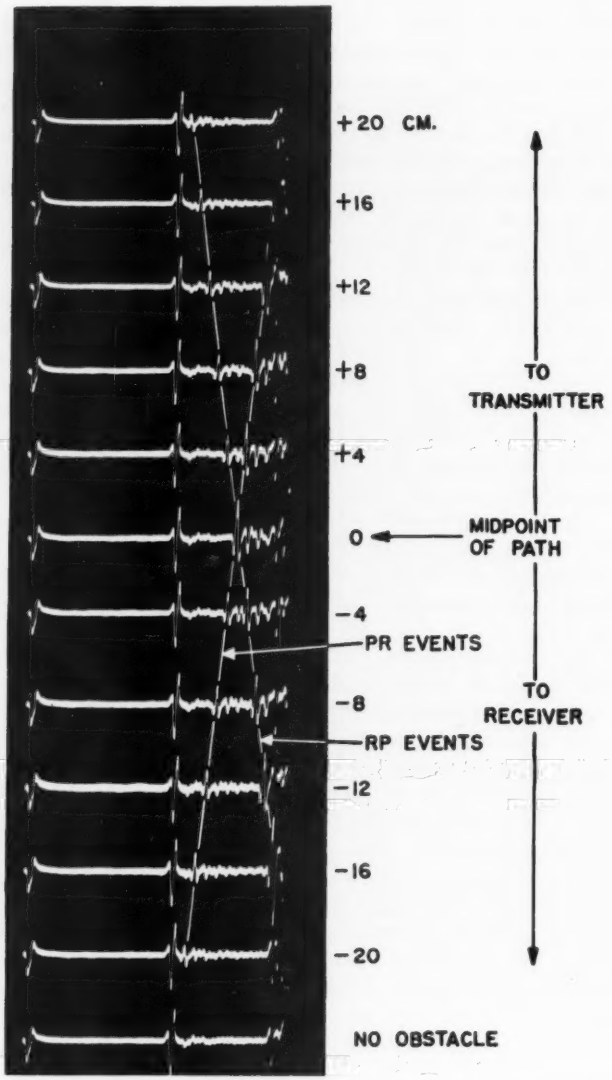


FIG. 2. Scattering from a brass obstacle between vertically directed $BaTiO_3$ transducers, located on the straight edge of a large aluminum sheet.

then the x-component of the motion at P is identical with the y-component at Q in the original orientation:

$$G_{xy}(P, Q) = G_{yx}(Q, P)$$
$$u_x(P, Q)f_x(P) = u_y(Q, P)f_y(Q)$$

An experimental verification of this type of reciprocity is given in Figure 3. In the same thin sheet of aluminum as above, a small rectangular hole was cut near the surface and the source transducer mounted to exert a horizontal force upon the sheet. The receiving transducer was placed 50 cm away and mounted to detect the normal component of the motion. An oil coupled cylindrical steel obstacle 0.40 cm diameter by 1.25 cm high was moved along the edge from receiver to transmitter as before in five cm steps. The observed motions are given in Figure 3a. The transducers were now interchanged so that the receiving transducer was located in the hole and detected the horizontal component of motion while the source was located at the former receiver site and exerted a vertical force. The observed motions for this case are given in Figure 3b. The signal in the two runs for image positions of obstacle are identical.

NON-RECIPROCAL CONFIGURATIONS

It will be noted that certain configurations of sources and receivers have a relationship that is undetermined from the reciprocity relations. We consider the case of a point source of force applied at P directed along x, and a receiver at Q that measures the y-component of motion, and perform the interchange without changing the orientation of the transducers. In the new configuration the source is at Q, still directed along x and the receiver is at P and still measures the y-component of the motion.

We can make no statement about the reciprocity since the scalar products of the vectors in equation (2) vanish. Similarly we seek a relationship between the Green's tensor terms $G_{yx}(P, Q)$ and $G_{yx}(Q, P)$ but our reciprocity theorem [equation (4)] makes no positive statement about the relation between these terms. Two examples serve to determine this relationship for seismology.

Case I. Lamb's Problem

In the case of a vertical (z) point source exciting motion as in Lamb's problem, the horizontal x-component of the motion at some point removed from the source has the following reciprocal relationship in cartesian coordinates

$$G_{xz}(P, Q) = -G_{xz}(Q, P).$$

We also note that in cylindrical coordinates (z, r)

$$G_{rz}(P, Q) = G_{rz}(Q, P).$$

Thus in this case a type of reciprocity relationship exists.

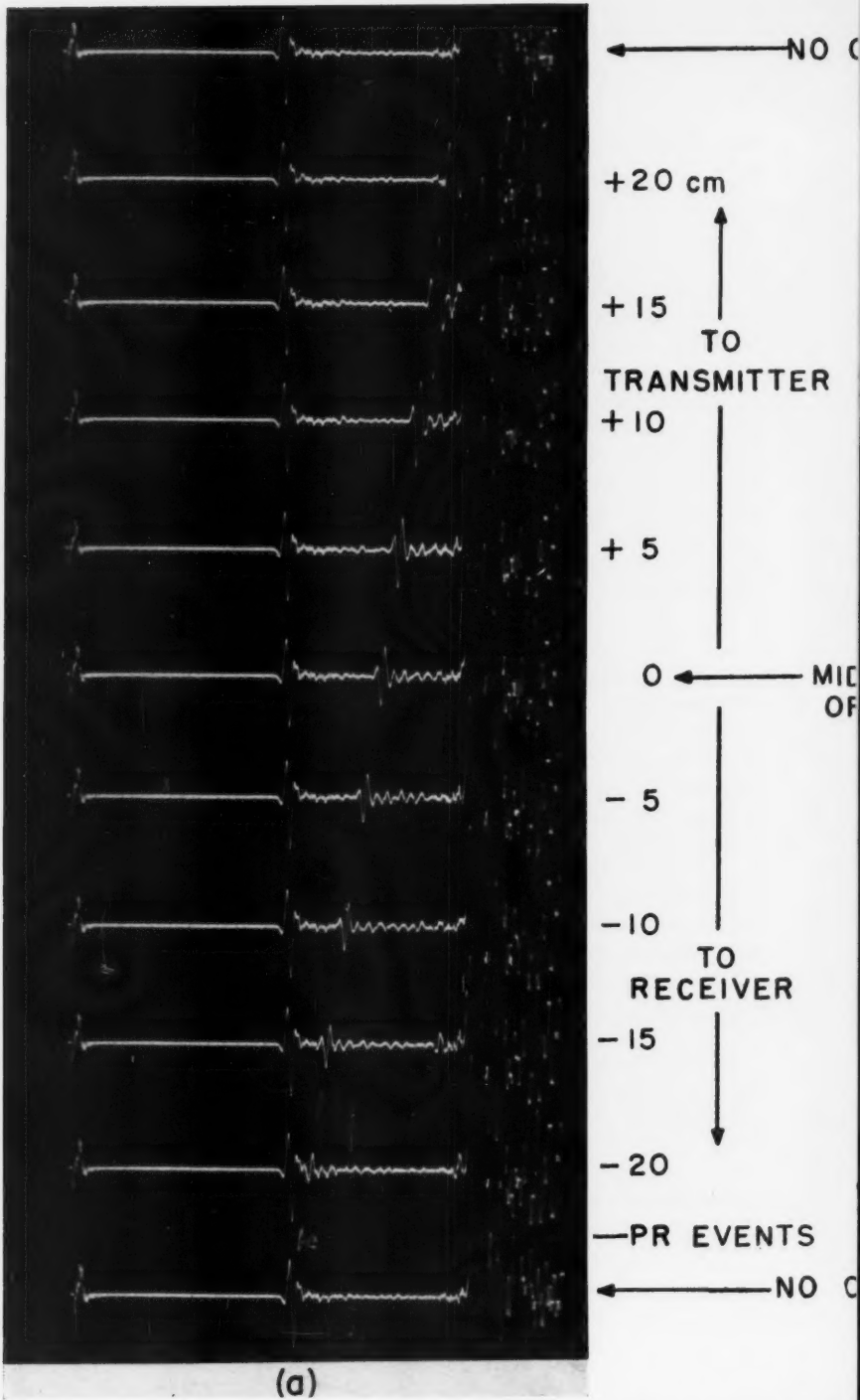
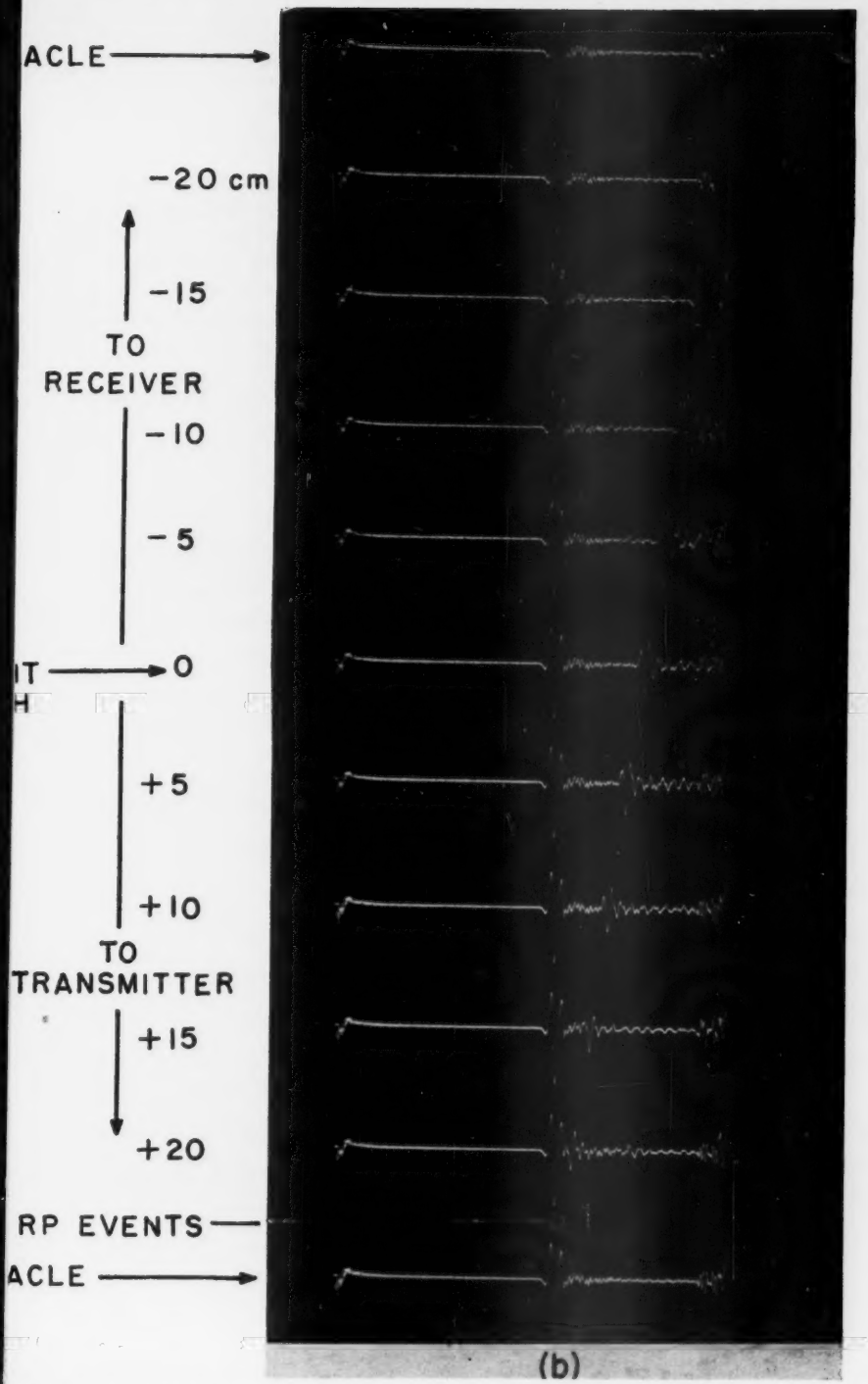


FIG. 3. Scattering from a steel obstacle between $BaTiO_3$ t

a) Vertical re

b) Horizontal



, located on the straight edge of a large aluminum sheet.

izontal source.

vertical source.

Case II

However the relationship given above for Lamb's problem is not general. Consider the case of the notched aluminum sheet of Case II of the preceding section with a vertical source, a horizontal receiver and an obstacle between them on the edge. As before, interchanging source and receiver while keeping their spatial orientations unchanged is equivalent to moving the obstacle to the image point. The comparison of the traces for the obstacle at two image points compares the quantities $G_{zz}(P, Q)$ and $-G_{zz}(Q, P)$. This record is precisely that of Figure 3a. The traces at these image points are not identical: for example the PR event at one obstacle station is not the same as the RP event at the image station for the obstacle. Hence we may write

$$G_{zz}(P, Q) \neq G_{zz}(Q, P).$$

SUMMARY

Reciprocity relations are of value to the seismologist. Under appropriate orientations of sources and receivers some proposed experimental measurements or calculations may be duplicates of other measurements or calculations and hence only one set need be taken. In the most general case of arbitrary inhomogeneity, anisotropy, and boundaries, the reciprocity relations are

$$G_{ij}(P, Q) = G_{ji}(Q, P)$$

and we note that

$$G_{ij}(P, Q) \neq G_{ij}(Q, P), \qquad i \neq j.$$

APPENDIX I

We take the time transform of the field equations (1) and write

$$\mathfrak{L}_{ij}\{\bar{u}_j(R; P)\} = \bar{f}_i(P) \tag{A1}$$

where $u_j(R; P)$ represents the vector u_j at R due to a point source $f(P)$ at P. The barred quantities are linear time transforms of the variables, taken by some procedure such as, for example, the Laplace or Fourier transforms. We form the difference of the products

$$\bar{u}_i(R; Q)\mathfrak{L}_{ij}[\bar{u}_j(R; P)] - \bar{u}_i(R; P)\mathfrak{L}_{ij}[\bar{u}_j(R; Q)] = \bar{u}_i(R; Q)\bar{f}_i(P) - \bar{u}_i(R; P)\bar{f}_i(Q). \tag{A2}$$

If the left-hand side can be written as the divergence of a vector $\overline{M}_{i,i}(R; Q, P)$ (we use this as the definition of the self-adjoint operator) then we can integrate both sides of equation (A1) over a volume V, having a boundary surface S, and enclosing the points R, P and Q. We then apply Gauss's Theorem, obtaining

$$\int_S \overline{M}_i n_i dS = \int_V \{\bar{u}_i(R; Q)\bar{f}_i(P) - \bar{u}_i(R; P)\bar{f}_i(Q)\} dV \tag{A3}$$

where the integration over V is taken over the points R

$$dV = dx_R dy_R dz_R.$$

If we assume homogeneous boundary conditions on the surface, i.e.,

$$\int \overline{M}_i n_i dS = 0$$

then

$$\int_V \{\bar{u}_i(R; Q)\bar{f}_i(P) - \bar{u}_i(R; P)\bar{f}_i(Q)\} dV = 0. \tag{A4}$$

Since we have point sources, that is $\bar{f}_i(P)$ and $\bar{f}_i(Q)$ are zero everywhere except at P and Q, the integration of equation (A4) yields

$$\bar{u}_i(P; Q)\bar{f}_i(P) = \bar{u}_i(Q; P)\bar{f}_i(Q) \tag{A5}$$

which is the reciprocity relation (2) of the text. Since equation (A5) holds for the equality of the time transforms $\bar{f}_i(P)$ and $\bar{f}_i(Q)$, it follows that reciprocity in the time domain holds if the time dependences of $f_i(P)$ and $f_i(Q)$ are the same.

In order to demonstrate that the elastodynamic case is included in the above reciprocity theorem, we note that the concomitant vector $\overline{M}_i$ is

$$\overline{M}_i(R; P, Q) = \bar{u}_j(R; Q)\bar{\tau}_{ij}(R; P) - \bar{u}_i(R; P)\bar{\tau}_{ij}(R; Q) \tag{A6}$$

where the operator $\mathfrak{L}_{ij}$ is given by equation (7). The divergence of the concomitant vector $\overline{M}_i$ is the desired value

$$\overline{M}_{i,i} = \bar{u}_i(R; Q)\bar{f}_i(R; P) - \bar{u}_i(R; P)\bar{f}_i(R; Q) \tag{A7}$$

by virtue of differentiating equation (A6) and making use of the identity

$$\bar{u}_{i,j}(R; Q)\bar{\tau}_{ij}(R; P) = \bar{u}_{i,j}(R; P)\tau_{ij}(R; Q) \tag{A8}$$

where we have used Hooke's Law, equation (6), and the symmetry conditions of equation (8).

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GEOPHYSICS, VOL. XXIV, NO. 4 (OCTOBER, 1959), PP. 692-705, 10 FIGS.

PHOTOMECHANICAL METHOD OF FREQUENCY ANALYSIS OF SEISMIC PULSES*

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ABSTRACT

The harmonic analysis of a seismic pulse performed by a photomechanical wave analyzer is analytically related to the Fourier integral analysis of this aperiodic pulse. The calculated integral spectra of three simple analytical pulses are compared to the spectra obtained from this wave analyzer. The integral analyses of two seismic pulses are compared to the harmonics obtained through numerical analysis.

The frequency range of the integral analysis which can be performed by this analyzer is from 5 to 300 cps. Integral analyses of recorded seismic pulses up to 6 inches long (0.10 sec) and with peak amplitudes up to 0.69 of an inch can be performed by this analyzer. From an evaluation of the equipment and operational errors involved in the measurements, the integral approximations obtained from the analyzer are estimated to be accurate on the average to within one db in the frequency range of 5 to 100 cps. For frequencies greater than 100 cps this accuracy will decrease. This is as great an accuracy as is usually obtained by numerical analysis.

THEORY

In comparing seismic pulses recorded under different conditions, from different sources, or by different recorders, it is necessary to have a uniform method of describing each pulse. Without some degree of uniformity it would be impossible to relate the results of various investigators. Most seismic recorders make a record of some function of ground motion (displacement, velocity or acceleration) against time. Such a description is reasonably complete, but is too complex to discuss in simple terms. It is more common to describe pulses in terms of their relative arrival times, duration, direction of particle motion, peak amplitudes, and the predominant "frequency" of the motion. It is this last property, frequency, which is the principal concern of this paper.

Strictly speaking, a transient pulse does not have the property of frequency, which implies repetition. It does not repeat itself. Frequency is a measuring device through which we regard a pulse to help in describing it; and the "frequency" of a transient pulse depends not only on the pulse but on the measuring system used. When one says that a pulse has a given frequency spectrum, what is meant is that within the time interval being considered the pulse resembles a repetitive pulse having this frequency spectrum.

This can be more clearly understood if one examines one of the processes by

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which frequency is commonly described, Fourier harmonic analysis.[1] Within certain limitations, most transient pulses encountered in practice can be described by an equation of the form

$$\phi(t) = A_0 + \sum_{n=1}^{\infty} A_n \cos(\omega_n t + \theta_n) \tag{1}$$

where A_0, A_n and θ_n are constants, $\omega_n = 2\pi n/T$, and T is the length of the interval being considered. A_n is called the amplitude of the component of frequency n/T. Selected values of A_n can be found by measuring the amplitude $\phi(t)$ of the

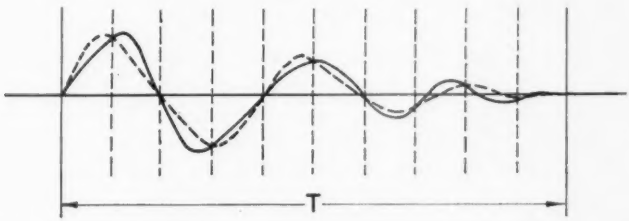


FIG. 1. Two pulses whose Fourier harmonic analyses are identical using the ten-ordinate method.

pulse at a number of times t, substituting these amplitudes and times into (1) and solving the resulting simultaneous equations. Standardized methods for carrying out such calculations are well known (see e.g. Scarborough 1930). A number of harmonics equal to half the number of points measured less one are calculated. The values of A_n and θ_n thus obtained describe a transient (Figure 1). The pulse can be approximated to any degree of closeness desired by measuring sufficiently many points. However, the method will not distinguish with only 11 measurements between two pulses such as the dashed and solid curves of Figure 1. Furthermore, if some other number of measurements are made, such as 9 or 13, a different spectrum will generally be obtained, as the points on the pulse which are fitted will be different. If the duration T of the pulse is changed to include more or less of the quiet interval before or after the pulse, even the frequencies constituting the spectrum will be changed. Equation 1 defines a pulse which repeats itself outside the interval being considered. It is only inside this interval that it describes the pulse.

However, any transient or aperiodic function, $\phi_a(t)$, exhibiting a finite number of discontinuities, maxima and minima in any finite interval, and whose absolute value integrated from minus infinity to plus infinity is finite, can be represented by a Fourier integral expansion:

[1] For a more complete mathematical treatment of frequency analysis see any standard text on the subject, e.g. Goldman (1948) or Scarborough (1930).

$$\phi_a(t) = \frac{1}{\pi}\int_0^\infty F(\omega)_a \cos\left[\omega t + \theta(\omega)\right]d\omega \tag{2}$$

where

$$F(\omega)_a = \left\{\left(\int_0^{T_\phi} \phi_a(t)\cos\omega t dt\right]^2 + \left[\int_0^{T_\phi} \phi_a(t)\sin\omega t dt\right]^2\right\}^{1/2} \tag{3}$$

$$-\tan\theta(\omega) = \frac{\int_0^{T_\phi} \phi_a(t)\sin\omega t dt}{\int_0^{T_\phi} \phi_a(t)\cos\omega t dt} \tag{4}$$

and $\omega = 2\pi f$, and $(0, T_\phi)$ is the finite interval in which $\phi_a(t)$ exists. In the above expressions the subscript "a" refers to aperiodic conditions. In equation 2, $F(\omega)_a$, is a continuous spectrum.

If an aperiodic pulse, $\phi_a(t)$, which is zero outside of a finite interval τ, is repeated with an impressed fundamental period T_p greater than τ, there will result a function which exhibits properties of both a periodic and an aperiodic function. The aperiodic pulse is here assumed to exist only in the interval $(0, T_p)$ which is equivalent to assuming that T_p equals T_ϕ. Under these assumptions the integral and harmonic analyses of this aperiodic pulse are related. The harmonic coefficients are

$$A_n = \frac{1}{T_p}\left\{\left[\int_0^{T_p} \phi_a(t)\cos\omega_n t dt\right]^2 + \left[\int_0^{T_p} \phi_a(t)\sin\omega_n t dt\right]^2\right\}^{1/2}. \tag{5}$$

The integral analysis of this pulse is given by equation 3 substituting T_p for T_ϕ. For those discrete frequencies of $F(\omega)_a$ identical to the harmonics of A_n, or for those frequencies $f_n = n/T_p$, equation 5 is related to the integral transform of this aperiodic pulse by the expression

$$F(\omega)_a = T_p A_n. \tag{6}$$

In practice, points on the Fourier integral spectrum are found by performing corresponding harmonic analyses. Any number of points can be obtained by performing sufficiently many and sufficiently thorough harmonic analyses.

APPARATUS

Numerical analysis is tedious. For that reason it is desirable to perform as many as possible of the operations by machine methods. A device for photomechanical harmonic analysis is shown in Figure 2. The pulse to be analyzed is traced onto a 1.38 inch wide strip of Mylar tape using a Leroy lettering pen filled with black paint. The pulse is extended as a straight line to a distance such that the pulse plus extension corresponds to the fundamental period T_p desired. The

whole trace is copied a second or additional times to make a total tape length of 18 to 27 inches. The area of the tape to one side of the traced line is painted black.

After the paint is dry, each tape is cleaned with turpentine and then spliced into a loop form. Mylar splicing tape is used for this purpose. It is placed on the non-painted side of the tape, since under tension better bonding can be had between two Mylar surfaces than between a Mylar surface and the paint. Tape splicing is a critical operation and considerable care has to be exercised.

The transient pulse is transformed into an electrical signal by drawing the

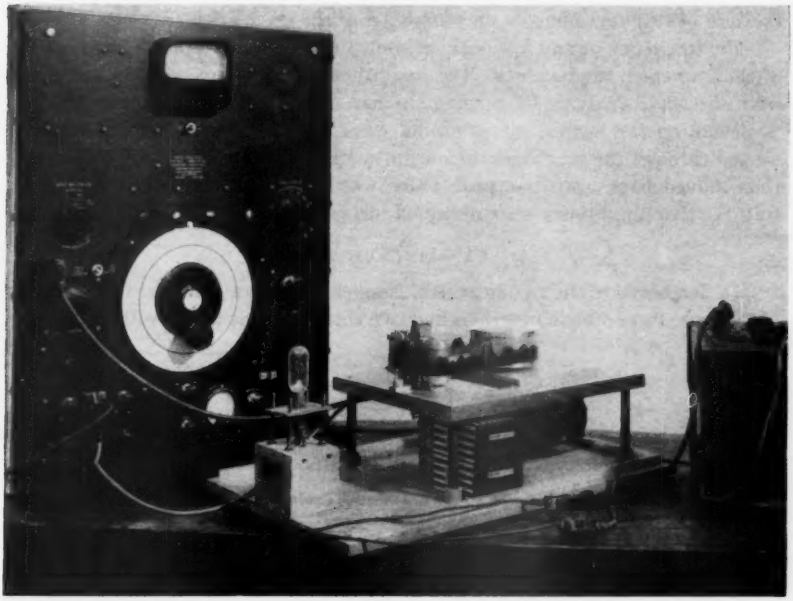


FIG. 2. The photomechanical wave analyzer.

tape past a 0.01 inch slit through which light shines on a Continental Electric Company CE-31V phototube. The half-blacked out tape causes the illuminated area of the tube to vary, producing a corresponding fluctuation in the phototube output. A capstan drive assembly is mounted on a movable base so that a range of tape lengths can be used. The capstan has a twelve inch circumference and is driven by a synchronous gear motor with an angular speed of 300 rpm, resulting in a tape speed of 60 inches per second. Since the bulk of the seismic pulses studied were recorded at about 15 inches per second, the analysis of these pulses will be run at about four times the original recording speed, and the observed frequency will be four times the actual frequency.

The phototube output is fed to a General Radio Type 736-A wave analyzer.

This is a heterodyne type of vacuum-tube voltmeter with a highly selective filter so that only voltages over a four cps band width are measured at any one setting. For pulses played back at four times the original recording speed, an equivalent band width of one cps of the pulse is being analyzed. The frequency range of this wave analyzer is from approximately 10 to 16,500 cps, and the amplitude range is from 30 microvolts to 300 volts. Care must be taken to use only pulse lengths of less than 15 inches on the tape, otherwise the individual harmonics will be so close together that they are not separable with the wave analyzer. The effect of having harmonics too closely spaced is to provide spurious peaks representing the sum of two harmonics in the pass-band of the wave analyzer simultaneously.

The frequency of any harmonic is known from the tape speed and the length of the impressed fundamental. The amplitude of any harmonic was determined from the wave analyzer by turning the fine tuning dial through this frequency while noting the output meter of the wave analyzer. As the fine tuning dial moved through the harmonic the output meter maximized. The tuning dial was then moved back until this peak value was maintained on the meter. In this way relative amplitudes were obtained for each harmonic.

EXPERIMENTAL DATA

To demonstrate the significance of frequency spectra obtained from this type of analysis, three simple functions and two actual seismic pulses will be discussed.

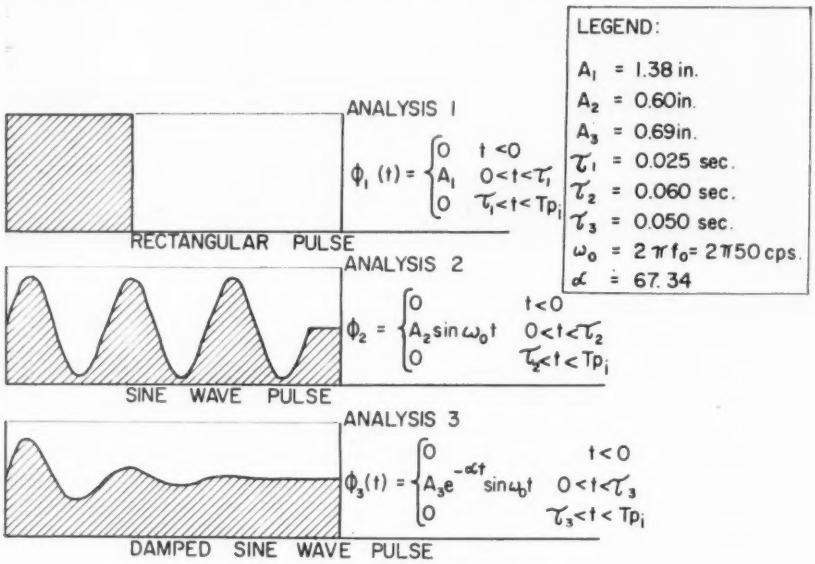

LEGEND:
A_1 = 1.38 in.
A_2 = 0.60in.
A_3 = 0.69in.
τ_1 = 0.025 sec.
τ_2 = 0.060 sec.
τ_3 = 0.050 sec.
$\omega_0 = 2\pi f_0 = 2\pi 50$ cps.
α = 67.34
ANALYSIS 1
$\phi_1(t) = \begin{cases} 0 & t<0 \\ A_1 & 0<t<\tau_1 \\ 0 & \tau_1<t<Tp_i \end{cases}$
RECTANGULAR PULSE
ANALYSIS 2
$\phi_2 = \begin{cases} 0 & t<0 \\ A_2 \sin\omega_0 t & 0<t<\tau_2 \\ 0 & \tau_2<t<Tp_i \end{cases}$
SINE WAVE PULSE
ANALYSIS 3
$\phi_3(t) = \begin{cases} 0 & t<0 \\ A_3 e^{-\alpha t} \sin\omega_0 t & 0<t<\tau_3 \\ 0 & \tau_3<t<Tp_i \end{cases}$
DAMPED SINE WAVE PULSE

FIG. 3. The simple pulses analyzed.

The three simple pulses treated are a rectangular pulse $\phi_1(t)$, three cycles of a sine wave $\phi_2(t)$, and a damped sine wave pulse $\phi_3(t)$ that attenuates to a small value in the interval considered. The graphical and analytical form of these simple pulses can be seen in Figure 3.

For each pulse six tape-loops were made with each loop containing a different impressed period. In the case of the rectangular pulse, the six tapes respectively

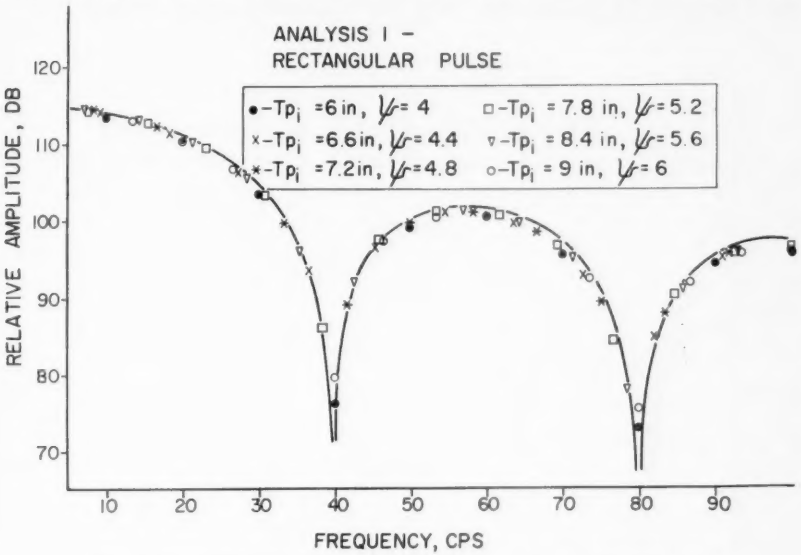


FIG. 4. Comparison of analyzer harmonic analysis with calculated transform of a rectangular pulse.

contained impressed periods of 4, 4.4, 4.8, 5.2, 5.6 and 6 times the duration of the rectangular pulse, which was 0.025 sec. For the sine wave pulse and damped sine wave pulse the impressed periods were 2, 2.2, 2.4, 2.6, 2.8 and 3 times the duration of the pulse which was 0.060 sec for $\phi_2(t)$ and 0.050 sec for $\phi_3(t)$.

Successive tapes for each of the three pulses were analyzed from approximately 10 to 100 cps. The observed data were corrected for non-linear frequency response of the General Radio analyzer at low frequencies. The observed values also were multiplied by an appropriate correction factor to eliminate the effect of the varying length of the quiet interval following the pulse. (The shorter the impressed period, the stronger is the total signal for a given pulse.)

Finally, the Fourier transform was calculated for each pulse assuming that the function was zero outside of the interval $(0, T_p)$. For expressing these calculations in db form, an arbitrary reference was assumed. The corrected data were plotted superimposed on the calculated Fourier transform (Figures 4, 5, 6). Since an

absolute analyzer calibration is unavailable, no absolute comparison is possible between the amplitudes of the observed and calculated data. A visual fit of the observed data to the transform has been made at the frequency of maximum amplitude.

The two seismic pulses (Figure 7) were analyzed in the same manner as the previously discussed pulses. The numerical method used was the 24-ordinate technique discussed by Scarborough (1930). For the numerical analysis in each case

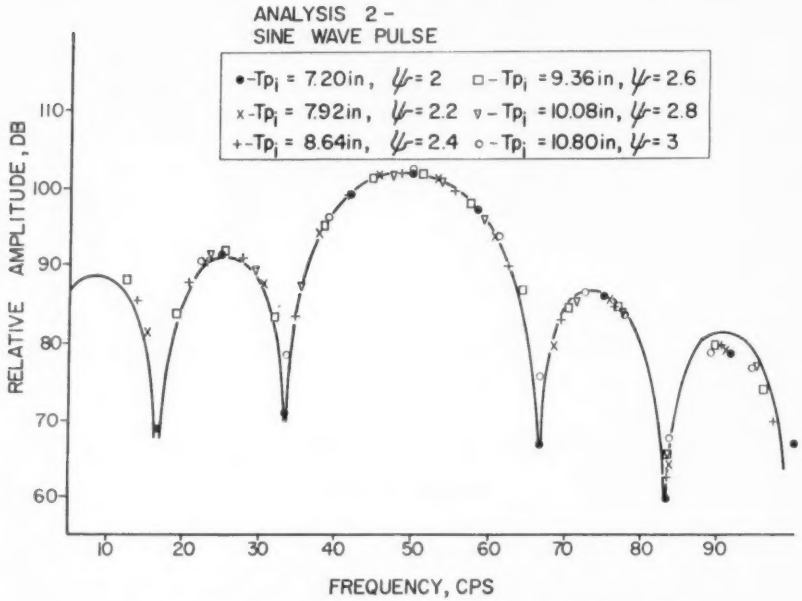


FIG. 5. Comparison of analyzer harmonic analysis with calculated transform of a sine wave pulse.

the fundamental period was chosen identical to the length of the seismic pulse under analysis, which is equivalent to letting $T_p = \tau$ of $\phi_a(t)$ with the analyzer. For the pulse $\phi_4(t)$ an additional analysis was made using a fundamental period of 6 inches (0.10 sec), which is identical to the analysis interval of the tape run on the analyzer. Figures 8 and 9 show the corrected analyzer data along with the various calculated line spectra for these two seismic pulses.

COMPARISON OF MACHINE AND MATHEMATICAL ANALYSIS

Previous theory has shown that the analyzer should give discrete frequencies on the continuous integral spectrum, but inspection of the analyses of the five

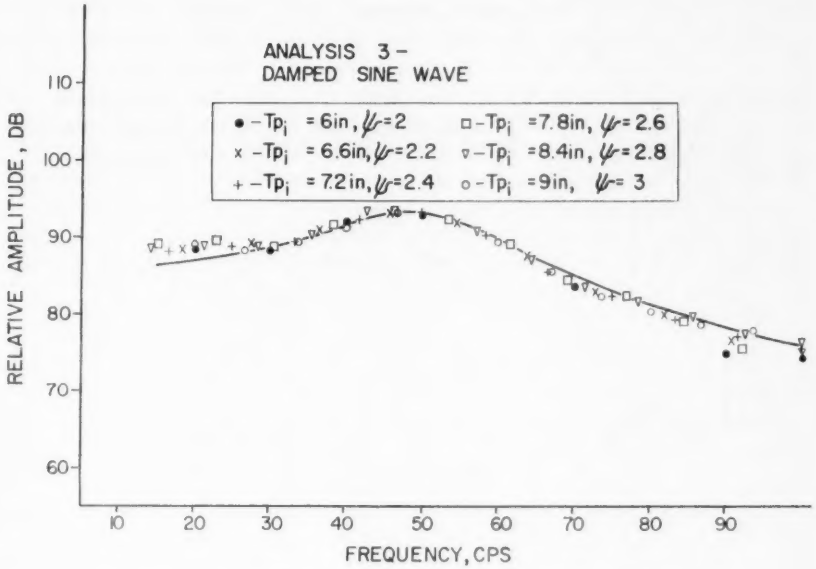
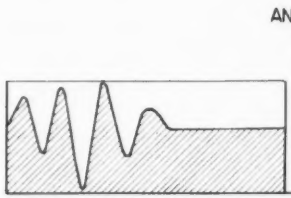
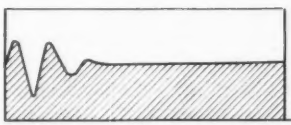


FIG. 6. Comparison of analyzer harmonic analysis with calculated transform of a damped sine wave.



ANALYSIS 4

Record No.	R–10
Recording Date	12 July 1951
Distance	196 ft.
Component	Longitudinal H_1 Away
Pulse Length	0.130 sec.
Pulse Interval	0.180 to 0.310 sec.
Source	1/4 stick dynamite



ANALYSIS 5

Record No.	R–42
Recording Date	27 November 1955
Distance	163.4 ft.
Component	Vertical V_3 Down
Pulse Length	0.050 sec.
Pulse Interval	0.140 to 0.190 sec.
Source	Wacker

FIG. 7. The seismic pulses analyzed.

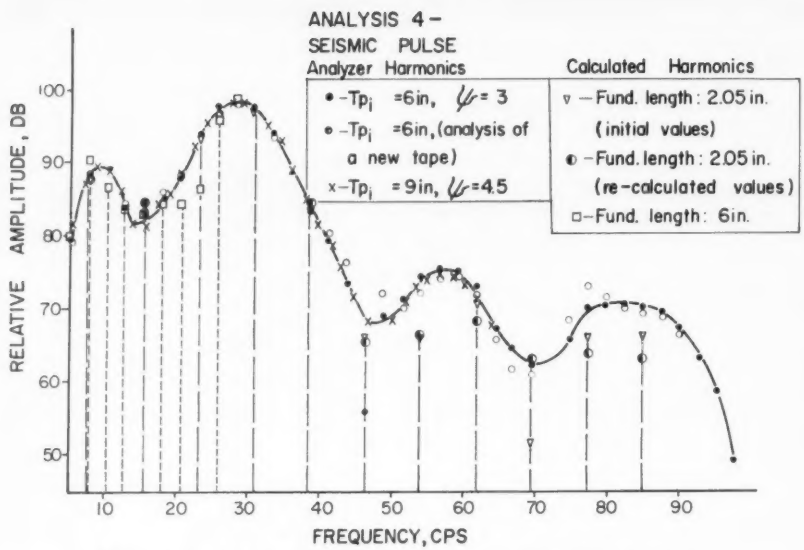


FIG. 8. Comparison of analyzer harmonic analysis with calculated harmonics of the seismic pulse, $\phi_4(t)$.

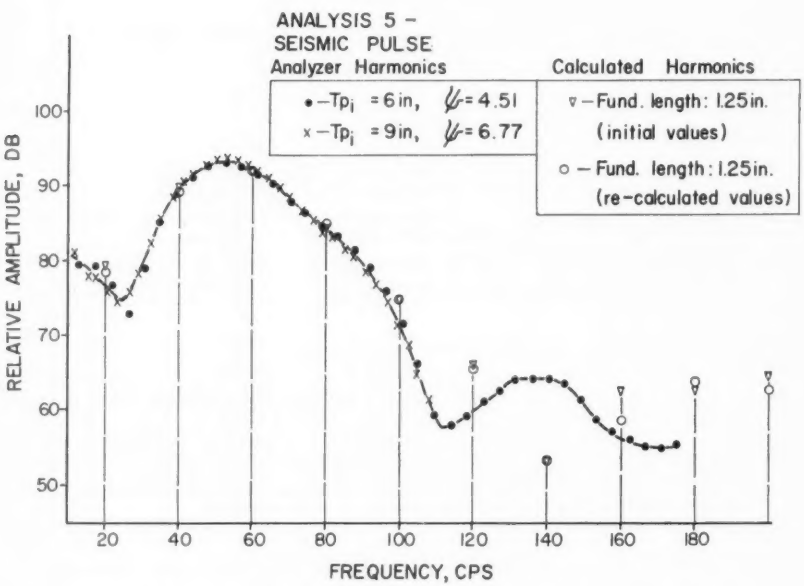


FIG. 9. Comparison of analyzer harmonic analysis with calculated harmonics of the seismic pulse, $\phi_5(t)$.

pulses shows that perfect agreement was not achieved. Especially apparent in the analysis of the simple pulses was a tendency for the analyzer to give lower readings compared to the calculated integral spectra as the frequency is increased (Figures 4, 5, 6).

Much of this distortion is believed to be due to the finite slit-width of the analyzer. Since the width of the slit is finite, a narrow segment of the curve is sampled at any particular time (Figure 10). Where the segment of the pulse in front of the slit is concave upwards less light falls on the phototube than should to represent properly the midpoint of the pulse. On the other hand, where the segment of the pulse in front of the slit is convex upwards more light falls on the phototube than should to represent properly the midpoint of the pulse. At points

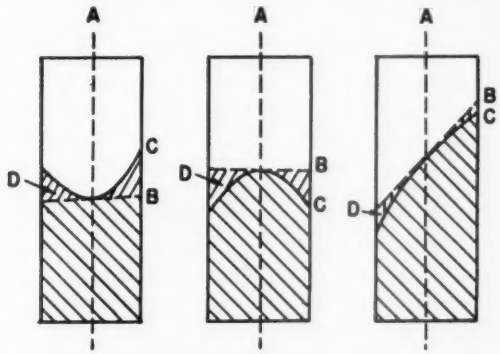


FIG. 10. Example of various curvatures in the finite slit of the analyzer.
A—midpoint of the slit
B—tangent line to the curve at the mid point
C—instantaneous portion of the curve in the slit
D—area erroneously analyzed
Actual width of the slit is 0.01 inch.

of maximum curvature of the pulse (usually peaks and troughs) the pulse shape as seen by the analyzer will be furthest from the actual pulse shape. Thus, the analyzer tends to round off the peaks and troughs with the amount of this round-off as a function of the curvature of the pulse. Therefore, high frequencies will be rounded off more than low frequencies, resulting in a systematic tendency to observe less energy than is actually contained in the pulse at the higher harmonics.

Generally the greatest scatter was exhibited by the tapes which had the longest impressed periods. The longer tapes require greater tension on the capstan drive assembly to prevent slipping. This results in greater friction between the capstan plus guide rollers and the tape. Thus, there is a greater tendency for the tape to pick up dirt from these parts, which reduces the transparency of the tape with time. This, in turn, reduces the output of the analyzer.

Inspection of the spectra for the seismic pulses (Figures 8, 9) reveals considerable difference between the analyzer data and all calculated harmonics. To investigate the cause of these discrepancies the Fourier harmonic calculations for analyses four and five were repeated using a new set of readings of ordinate values obtained from the seismic pulses. The ordinate values generally can not be read closer than one part in a hundred (or ± 0.01 inch), and for those ordinate values in regions of maximum slope this read-off accuracy is reduced to about five parts in a hundred. The reason for this is that, as the slope of the seismic pulse increases, the pulse approaches tangentially to an ordinate value and the ordinate no longer

TABLE I

REPRODUCIBILITY OF DATA

Difference of relative amplitude values for reruns of analyzer and calculated harmonics (Analysis 4).

Frequency	Analyzer	Calculated
7.7 cps	0.2 db	0.1 db
15.4	0.3	0.1
23.1	0.3	0.3
30.8	0.9	0.2
38.5	0.4	0.2
46.2	11.4*	0.4
53.9	2.3	0.2
61.6	1.1	2.5
69.3	1.4	11.5
77.0	2.9	2.2
84.7	0.9	3.0

* Meter needle unsteady

intersects the seismic pulse at a distinctly recognizable point but in a region. Therefore, one would expect greater error to be introduced in reading off ordinate values in these regions. The slopes of $\phi_4(t)$ are greater than those of $\phi_5(t)$ and a greater difference was observed between the two sets of ordinate values for analysis four than for analysis five. This difference, in turn, is reflected in a greater discrepancy between the amplitudes of the high harmonics for the original. and recalculations of analysis four than for the corresponding situation in analysis five. Quantitatively, this can be seen by comparing these differences for analysis four as contained in Figure 8 with the corresponding difference in Figure 9.

Similarly, to test analyzer repeatability a new tape was constructed and run for analysis four. Table I shows the decibel differences of the initial and recalculated harmonics as compared to the differences for the frequencies of the analyzer run and re-run. Below 43 cps, where good correlation exists between the calculated harmonics and the analyzer data, low differences were found for both sets of data. For those harmonics for which poor correlation exists, lower reproducibility (as indicated by large difference values) was found.

For the previously discussed calculations the length of the analysis interval

was chosen identical to the length of the pulse under analysis. As the length of the analysis interval is reduced approaching the length of the pulse, the approximation to an integral analysis becomes poorer. Therefore, the harmonic calculations for analysis four were repeated assuming an analysis-interval length of six inches (0.10 sec), which is identical to the impressed period of a tape run on the analyzer. An examination of these harmonics as contained in Figure 8 shows even greater discrepancies than the initial calculations. An explanation for this difference may be that with this six-inch fundamental 62.5 percent of the ordinate values (or 15 ordinates) fall outside of the length of the pulse and are thus zero. This leaves 37.5 percent of the ordinates (or nine ordinates) for calculating the harmonic spectrum of the pulse. It appears that nine ordinates are an insufficient sample for accurately calculating the harmonic content of the pulse.

It is concluded that the lack of correlation between the analyzer data and the calculated data is primarily due to measuring inaccuracies in the numerical analysis procedure used. When the analysis interval for the numerical calculations is equal to the length of the pulse under investigation it is difficult to read off accurately ordinate values in regions of steep slope. On the other hand, if the analsis interval is considerably greater than the length of the pulse under analysis, too few non-zero ordinates are available for the calculation.

SOURCES OF ERROR AND ACCURACY OF THE MEASUREMENTS

In addition to the sources of error outlined in earlier sections, part of the scatter contained in the analyzer data can be expected to result from sources of error inherent in the equipment and its operation. Due to the absence of a system calibration, it is impossible to assess the magnitude of the total system error and hence determine the absolute accuracy of the analyzer. However, certain real and potential sources of error are known and are discussed below.

The voltage accuracy of the General Radio wave analyzer according to the manufacturer's specifications is within 5 percent or ± 0.5 db. This inherent source of error was minimized for a given pulse by standardizing analysis procedure and by performing the various analyses as expeditiously as possible.

Two potential sources of error result from variations in lamp voltage and in B-supply voltage of the phototube. The ac output of the phototube was relatively insensitive to B-supply voltage, but a 0.2 volt change in the rated lamp voltage (8.5 volts) results in a measured change of 0.5 db in analyzer output. These voltages were checked before and after each analysis. Errors due to voltage variations are believed to be negligible.

Operational errors are difficult to assess quantitatively . However, the observation was made that for long duration runs on the analyzer the tape picked up sufficient powdered aluminum from the capstan drive assembly and guide rollers to account for about 0.3 db decrease in the amplitude of a harmonic read near the end of an analysis as compared to its value at the start of the analysis.

A poor loop splice can introduce signals at frequencies corresponding to the

total tape length (two or more times the length of the repetition interval) and its harmonics. These spurious signals result when the axis of the trace is not parallel to the center of the tape, so that its ends do not join evenly, or when the several tracings of the pulse are not identical. The result is an oscillation of the output-voltmeter needle, making it difficult for the analyst to read the meter closer than ± 0.2 db.

A source of error unrelated to the analysis itself is introduced if the recording speed of the original seismogram from which the tape was made is not constant. This results in a shift of some of the energy up or down the frequency spectrum proportional to the variation in the original recording speed. Variation in the playback speed will have the same effect. A small amount of slippage of the film on the capstan can occasionally be observed using a stroboscope. However, it is irregular in amount, and believed to contribute only to the small unsteadiness of the voltmeter needle on the wave analyzer.

At very high frequencies problems like the failure of the optical slit to be parallel, and variations in sensitivity of the phototube surface probably become important. This effect is estimated to be unimportant below 100 cps. It is important, however, to shield the phototube from extraneous light sources such as sunlight, and to keep the existing light far enough away that the light rays are approximately parallel and illuminate the slit evenly. If the light was brought much within eight inches of the slit, harmonic distortion was suspected, so the light was kept at this distance during all runs.

An overall estimate of the accuracy of the analyzer approximation to an integral analysis can be obtained from the calculated and observed data on the three analytical pulses. With these pulses it was possible to calculate what the integral spectrum should be. Therefore, any deviation of the observed data from the calculated data is a measure of the inaccuracy of the method. Here again, the absence of an absolute system calibration prevents this estimate of inaccuracy from being absolute. Using the calculated integral spectrum as a standard, the magnitude of the scatter of the analyzer data from this standard was measured and averaged for the rectangular pulse, sine wave pulse and damped sine wave pulse. These average values are based on the assumed fit of the analyzer data to the calculated data. If a better fit can be made these averages will be less. The result of these measurements are listed below:

	Average Deviation	Maximum Deviation and Frequency at Which It Occurred
(1) Rectangular Pulse	0.7 db	+2.2 db (81.8 cps)
(2) Sine-Wave Pulse	0.7 db	−3.2 db (97.2 cps)
(3) Damped Sine-Wave Pulse	0.8 db	−3.6 db (90.0 cps)

These measurements did not include, in the case of the rectangular pulse and sine-wave pulse, the magnitude of the scatter where the amplitude of the theoretical integral curve went to zero. At these frequencies (40 cps and 80 cps for the rectangular pulse and 16.7, 33.4, 66.8 and 83.5 cps for the sine wave pulse), the analyzer is incapable of presenting an accurate approximation.

CONCLUSIONS

It is concluded that within the frequency range from five to one hundred cps the integral approximations obtained from the analyzer are accurate on the average to within about one db. At frequencies greater than one hundred cps the accuracy will decrease. This is just as great an accuracy as is usually attained by numerical analysis, due to expectable inaccuracy in measuring amplitudes on the records themselves.

The purpose of this analyzer is to serve as a tool in studying seismic pulses. It provides a useful, reproducible means of describing such pulses. It has been used in investigations reported or being reported separately by Howell and Mathur (1956) and by Andrews (1957).

ACKNOWLEDGMENTS

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GEOPHYSICS, VOL. XXIV, NO. 4 (OCTOBER, 1959), PP. 706–724, 20 FIGS.

THE CORRECTION OF SEISMIC TIME MAPS FOR LATERAL VARIATION IN VELOCITY BENEATH THE LOW VELOCITY LAYER*

C. H. ACHESON†

ABSTRACT

Lateral variation in velocity beneath the low velocity layer often causes time anomalies that obscure the true structural picture. A method of correction to a deep datum has been developed to minimize the spurious anomalies without affecting those caused by structure. This method makes use of the discovery that for any particular well in Western Canada, there exists a simple exponential relationship between time and depth so that the results of relatively shallow core hole velocity surveys can often be extrapolated to predict times to much greater depths. An example is given to show how this method was applied successfully to a particular problem area in Western Canada. It has since been used in several other places.

INTRODUCTION

The basic values in a reflection time map represent echo times from geological discontinuities to a horizontal datum level. These are simply the reflection times observed at the surface, corrected for elapsed time between surface and datum.

In the detailed calculation of such corrections, it is usual to assume that velocities below the weathered layer are constant. In many areas this assumption is roughly correct and produces reasonable time structure maps. Nevertheless, subweathering velocities are always variable, and the same method that is successful where the changes can be ignored, fails to correct adequately where variation is intense. In some areas, false anomalies several hundred ft in relief have been introduced by failure to correct for lateral variation in velocity beneath the low velocity layer.

Several authors have noted the spurious representation of surface topography in time maps in hilly country. As the result of investigations, M. B. Widess (1946, 1952) concluded that although velocity variation may be partly due to overburden effect, in many areas it is probably caused by other factors. More recently, Baillie and Rozsa (1955) have proposed an interesting method of correction for "load effect" to which they attribute the spurious features of a map in Canada.

Lateral variation is closely associated with vertical variation of velocity. From time to time, empirical formulas between velocity and depth have been proposed by Banta (1941), Haskell (1941), Stulken (1941), Narvarte (1946), Sparkes (1942), West (1950), and others. As the result of an extensive statistical study, L. Y. Faust (1951) concluded that velocity in an average section of sand and shale is proportional to the sixth root of the product of depth and geologic

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age. This formula was later modified to include a lithologic factor (Faust, 1953). Theory and experiment on the velocity of sound through variously packed granular substances have been discussed by Iida (1939), Gassman (1951), White and Sengbush (1953), and Patterson (1954). Iida's early conclusion that the velocity of sound in simply packed granular substances varies as the sixth root of depth, seems to be in general agreement with later investigations.

In 1952 Imperial Oil Limited investigated a problem area in south central Alberta where spurious time anomalies obscure the structural picture. Core hole velocity surveys indicated intense lateral variation in velocity below the low velocity layer, which corresponds only roughly to surface topography. As will be shown, the intensity of velocity variation decreases in such a way, that it can be ignored below a certain depth. A method of correction to a deep datum was developed, involving considerable extrapolation of the time depth curves of available core hole velocity surveys. This was made possible by the discovery that a simple exponential relationship exists between time and depth for all core holes in the area. Later investigation showed that the same general relationship applies to all wells in the Western Canada Basin, hence, the method has widespread application. It is interesting to note that the relationship, obtained independently, is similar to formulas published by Faust.

INVESTIGATION OF A PROBLEM AREA IN SOUTH CENTRAL ALBERTA

In 1952 a reflection survey carried out in south central Alberta could not be reconciled with geology. A well drilled at *A*, to test the seismic high, shown in the time map in Figure 1, encountered formation tops several hundred ft lower than expected.

The seismic high resembles surface topography (Figure 2), which does not conform to structure.

Results of a core hole velocity survey carried out to obtain a better correction for the map, showed that pronounced lateral variation in velocity continues for more than seven hundred ft below the low velocity layer. The nature of this variation is now described in detail.

Lateral Variation in Velocity

In this area, surface elevations are between 2,600 and 3,200 ft, and the low velocity layer is less than 100 ft thick. Core hole velocity surveys were carried out to penetrate to a datum level at 2,500 ft elevation, which is everywhere below the base of the low velocity layer. To accomplish this, data were measured to various depths, from 150 ft to 700 ft below surface. Figure 3 shows the location of the core hole velocity surveys.

Figures 4 and 5 are time depth curves and corresponding velocity depth curves for *P*, *Q*, *R*, *S* and *T*.

Isovelocity surfaces, deduced from the velocity depth curves, show that pronounced lateral variation in velocity persists below the low velocity layer, at

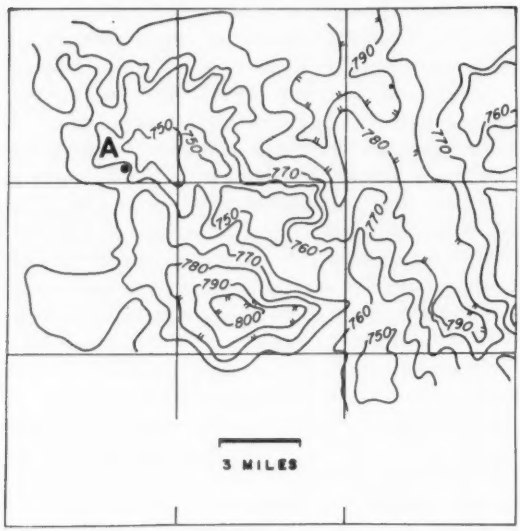

FIG. 1. Conventional seismic time map of the Viking formation (Cretaceous) corrected to 2,700 ft datum elevation at a constant datum velocity of 7,000 per second. Contour interval ten milliseconds. The large seismic high near *A* was proved spurious by drilling.

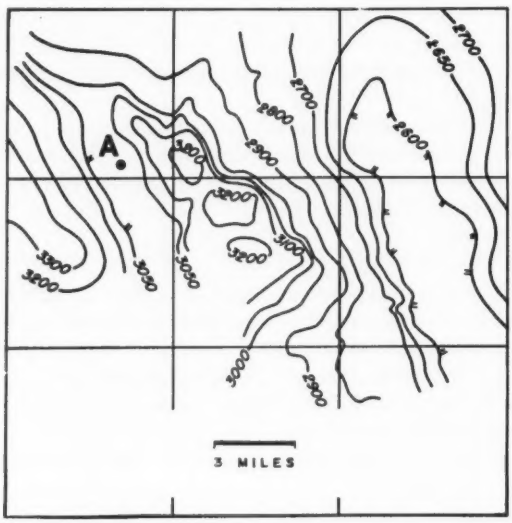

FIG. 2. Surface topography. Contour interval 100 ft. The range of hills adjacent to *A* roughly resembles the spurious seismic anomaly in Figure 1.

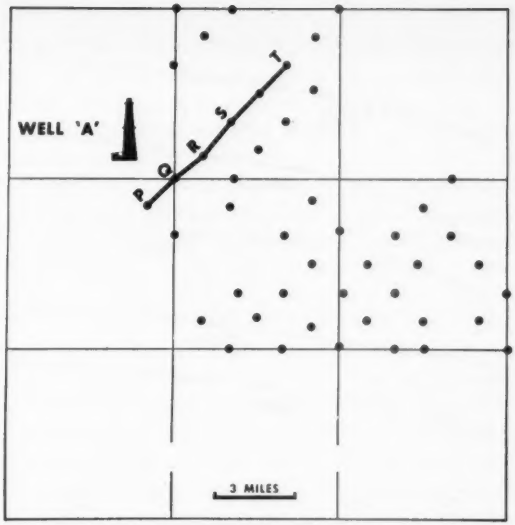

FIG. 3. Location of core hole velocity surveys. More than forty core hole velocity surveys were conducted to obtain accurate time depth data to the 2,500 ft datum elevation. *PT* is a representative profile used in this paper for discussion purposes.

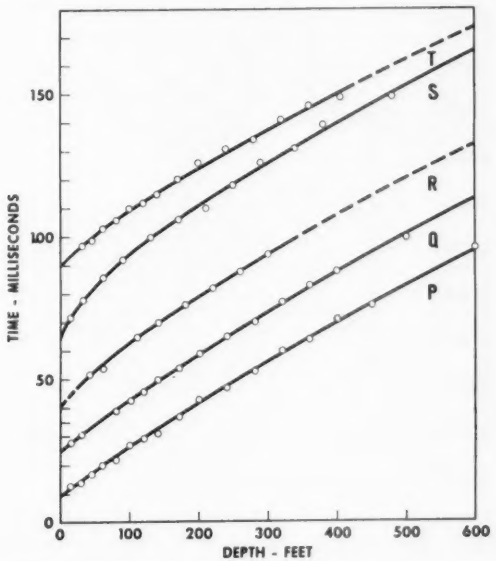

FIG. 4. Time depth curves—profile *PT*. The time scale is relative.

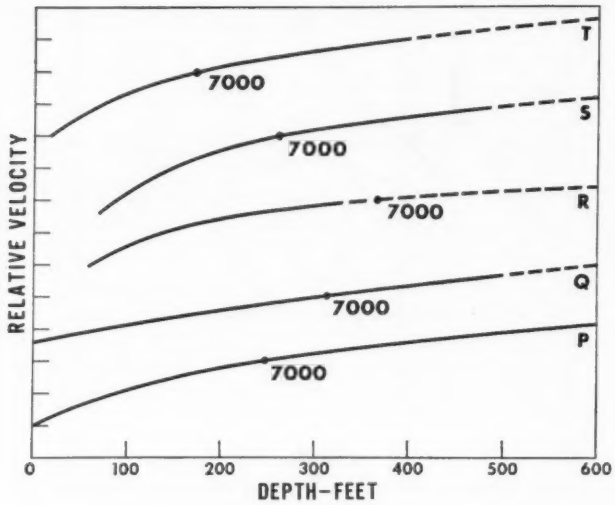

FIG. 5. Instantaneous velocity depth curves—profile *PT*. Numbers on the curves indicate velocity values in ft per second. The relative velocity scale is in intervals of 1,000 ft/sec.

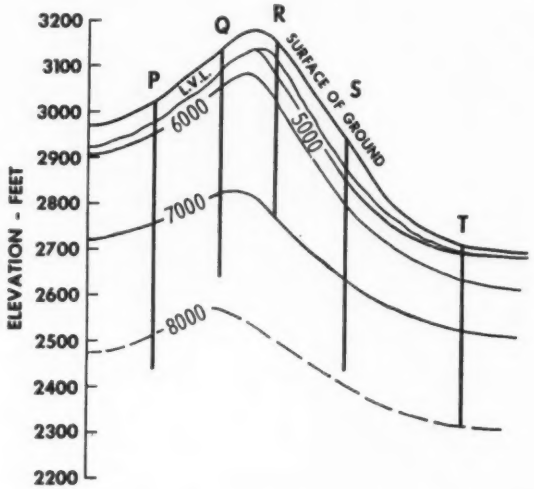

FIG. 6. Diagram to illustrate isovelocity surfaces—profile *PT*. Undulations in these surfaces indicate lateral variation in velocity to depths exceeding 700 ft. Though in this diagram the isovelocity surfaces follow surface topography, they diverge from it in other parts of the area.

least as far as the 2,500 ft datum. Well surveys indicate further, that velocity variation is effective even beyond this depth. The double time from 2,500 ft elevation to 1,000 ft elevation is 12 milliseconds greater at *A*, than at a well six miles distant. The double time between 1,000 ft and sea level, on the other hand, is virtually the same at each well.

Further study indicated that the isovelocity surfaces tend to conform to each other though they do not necessarily follow surface topography. Though the anomalous velocity condition at depths below 700 ft influences time maps, eventually at greater depths its effect becomes negligible.

DISCOVERY OF THE TIME DEPTH RELATION $t=az^n+b$

Before the core holes could be used for correction purposes, their time depth curves required extrapolation. In the search for a suitable method, a simple exponential relation was found to exist between time and depth. We shall now show that the equation of the time depth curve at well *A* is approximately $t=0.268z^{.895}$ where t is in milliseconds and z is in ft. As will be explained below, later studies show that a general relationship $t=az^n+b$ holds throughout the Western Canada Basin where a, b and n are constants for any one gross lithology at any one place. Further, n varies so slowly between the values 0.87 and 0.97, that for many practical purposes it is convenient to ignore the variation and assume that n is equal to 0.91 throughout.

The relationship was found by plotting time against depth on bilogarithmic paper. The time depth curve as shown in Figure 7, consists of two straight lines that intersect at a depth of about 4,000 ft, where there is a major unconformity

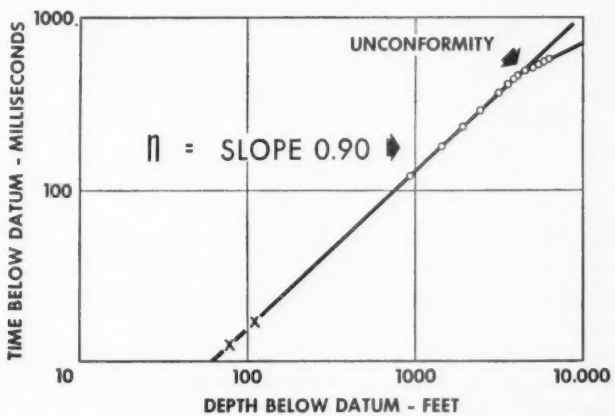

FIG. 7. Time depth plot of well *A* on bilogarithmic paper. Elev. K.B. 3,049 ft; elev. datum 2,971 ft. The curve is continuous from surface to the Paleozoic unconformity, and obeys the formula $t=.268\ z^{.895}$ where t is in milliseconds and z is in feet.

between clastics in the Cretaceous and carbonate rocks in the Paleozoic. Since this correction is limited to velocity effects in the first few thousand ft, only the first straight line will be considered.

Now a straight line on bilogarithmic paper has the equation:

$$\log t = n \log z + \log a \tag{1}$$

which can be written also:

$$t = az^n. \tag{2}$$

Examination of equation (1) indicates that the slope n is equal to the difference in the logarithms of t at the points ten z and z. Its value can be determined graphically by drawing a line parallel to the time depth curve through 10, 10; noting its intercept t at abscissa 100, and using the formula, $n = \log t - 1$.

The equation for the time depth curve can be found by several methods, including least squares. In this case, an accurate equation between time t in milliseconds, and depth z in ft is:

$$t = .268z^{.895}. \tag{3}$$

Calculated and observed values are compared below in Table 1. The origin of coordinates of time and depth is the base of the low velocity layer (elevation

TABLE 1

Depth	Observed Time	Calculated Time
17 ft	4 milliseconds	3 milliseconds
67	11	12
92	14	15
117	18	19
928	118	121
1,428	177	178
1,928	232	233
2,433	288	288
3,183	365	366
3,558	405	404
3,783	428	427
3,813	429	430

2,971 ft) which is 78 ft below the kelly bushing elevation. Values in the near surface were obtained from a shallow core hole velocity survey shot at the well for low velocity layer control, and have been adjusted to the same reference level as the rest of the data.

The standard deviation between observed and calculated times (as expressed by the square root of the sum of the squares of the deviations divided by the number of variates) is plus or minus 1.2 milliseconds.

The following values were calculated for the first few hundred ft in well A, where no measured control exists.

Results are shown graphically on Figure 8.

TABLE 2

Depth—Ft	Time—Milliseconds
25	5
50	9
100	17
200	31
300	44
400	57
500	70

Velocity Variation with Depth

Restating the general formula $t = az^{.91} + b$ as $t = az^{10/11} + b$, and differentiating,

$$V = \frac{1{,}100}{a} z^{1/11} \tag{4}$$

where V is in ft per second, and z is in ft. This suggests that velocity variation is most intense in the near surface. Using the typical formula $V = 5{,}200\ z^{1/11}$ as an example, it is obvious that velocity change in the first thousand ft greatly exceeds that in the next nine thousand—as shown in Table 3.

Assuming that a remains fairly constant in a small area, the velocity variation is somewhat as shown in Figure 9. The marked widening of the interval between successively deeper isovelocity surfaces, should be noted particularly, for it indicates decrease in the intensity of velocity variation, both vertical and lateral, with increasing depth.

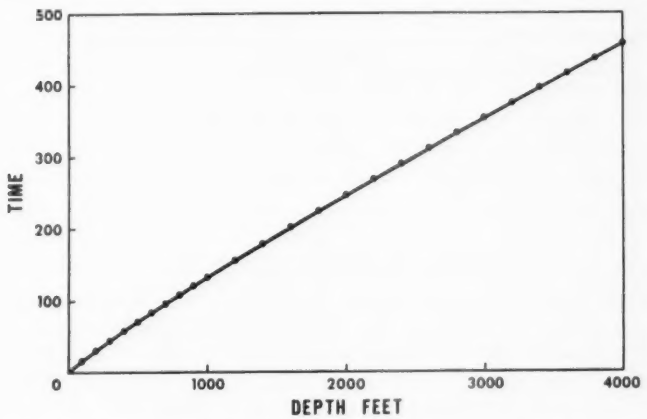

FIG. 8. Time depth curve for well A, calculated by formula $t = .268z^{.896}$, indicates the shape of the curve in the near surface, where no measured data exist.

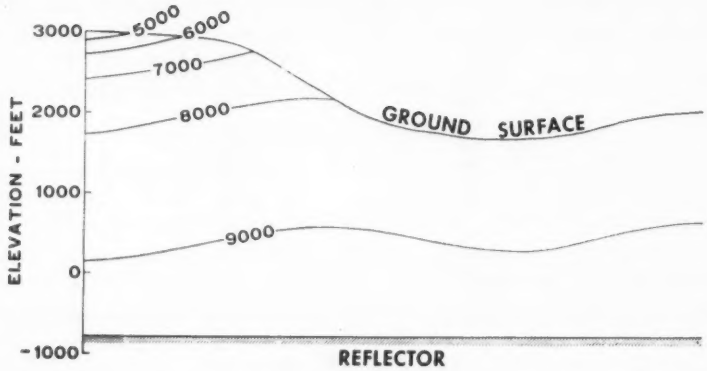

FIG. 9. Schematic diagram to illustrate velocity variation in an area. Isovelocity surfaces tend to conform to each other, though not necessarily to the ground surface. Widening of the interval between successively deeper isovelocity surfaces indicates decrease in the intensity of velocity variation, both vertical and lateral, with decreasing depth.

RELATIONSHIPS BETWEEN TIME DEPTH CURVES AT CORE HOLES

It can be shown that the time depth curves at the core holes are all simply related to each other, and to the time depth curve at well A. In order to demonstrate this, core hole P and well A are now compared. Data for core hole P, are furnished in Table 4.

It is possible to interpolate a set of values at even hundreds of ft, from the time depth curve. These are compared in Table 5 with data deduced by formula for well A.

The time depth curve for core hole P indicates that 6,000 ft/sec is attained at the point 100 ft, 23 milliseconds. The curve for the well shows that 6,000 ft/sec is attained at 32 ft, 6 milliseconds. The time depth curve for the core hole, below the isovelocity surface, is obtained by subtracting 100 ft and 23 milliseconds from the observed values; and a similar curve for the well is calculated from its time depth curves by subtracting 32 ft and 6 milliseconds. These revised time depth

TABLE 3

VELOCITY AND DEPTH VALUES ACCORDING TO THE FORMULA $V = 5{,}200\ z^{1/11}$

z—Ft	V—Ft per Second
1	5,200
10	6,400
100	8,000
1,000	9,900
10,000	12,200

TABLE 4
CORE HOLE *P*

x	*t*
18 ft	8 milliseconds
32	11
81	19
100	23
120	26
140	30
170	34
200	39
240	45
280	50
320	57
360	63
500	80

TABLE 5
TIME AND DEPTH BELOW SURFACE

Depth	Time	
	Core Hole *P*	Well *A*
100 ft	23 milliseconds	17 milliseconds
200	39	31
300	54	44
400	67	57

TABLE 6
TIME AND DEPTH BELOW THE 6,000 FT/SEC ISOVELOCITY SURFACES

Depth	Time	
	Core Hole *P*	Well *A*
100 ft	16 milliseconds	15 milliseconds
200	31	30
300	44	43
400	58	57

curves suggest a strong relationship between the data at each location, as shown in Table 6.

Figure 10 shows that the time depth curves for the five core holes in profile *PT* can be made to coincide with that of the well by choosing the common reference isovelocity surface 7,000 ft/sec at the depth indicated by the vertical line. If one isovelocity surface occurs at a depth common to all these shifted curves, then the fact that they fit each other indicates that all other isovelocity surfaces occur at common depths.

The dashed lines in Figure 10 suggest how the data might be extrapolated.

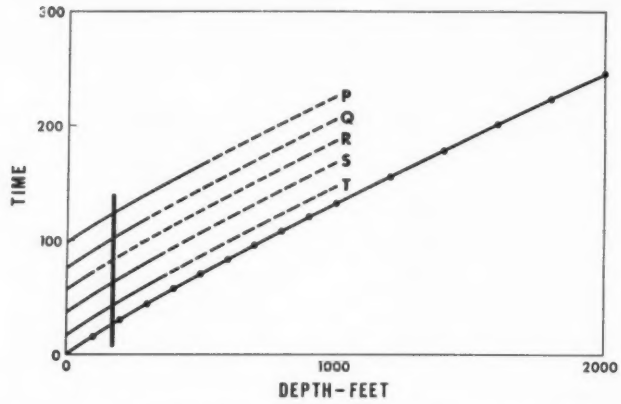

FIG. 10. Comparison of time depth curves for well A and core holes P to T each shifted laterally along depth axis so that the vertical line intersects all curves at point where velocity is 7,000 ft/sec Time scale is relative.

This method was used in 1952, but has since been superseded by a more elegant technique, which will be discussed below.

EXTENSION OF THE TIME DEPTH RELATION TO OTHER AREAS

Experience shows that the time depth curves for the Cretaceous section in Western Canada invariably plot as straight lines on bilogarithmic paper, whose slope values lie within a narrow range from 0.87 to 0.97.

Time depth curves for two Alberta wells a hundred miles apart are shown in Figure 11, to illustrate the very small difference in their slope values, n.

As more wells were investigated it became apparent that for wide areas n is

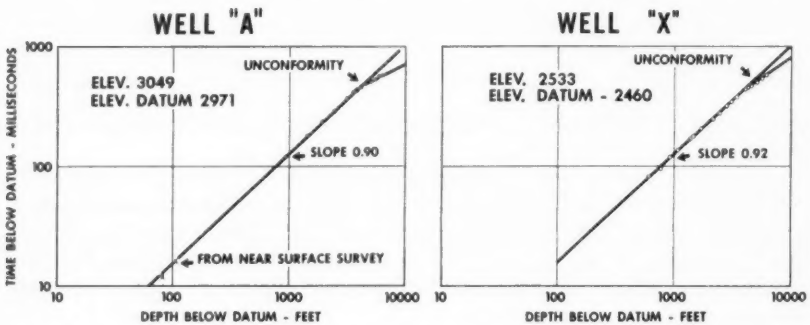

FIG. 11. Comparison of time depth curves for two Alberta wells 100 miles apart. Bilogarithmic plots show that each obeys the relationship $t = az^n$ where n is approximately 0.9.

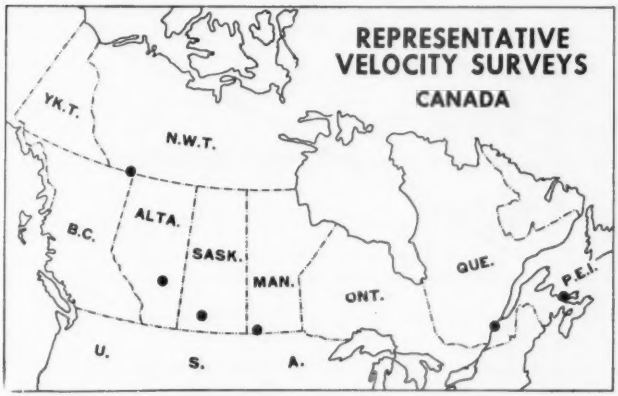

FIG. 12. Index map showing location of representative velocity surveys in Eastern and Western Canada.

approximately equal to 0.91. A special type of graph paper was devised, therefore, on which the time depth curves would plot as straight lines. This has been called exponential paper, for although the time scale is linear, the depth scale represents distances raised to the power 0.91. On this type of paper, time depth curves for over 1,500 wells in the Western Canada Basin are almost invariably straight lines for thousands of ft. Examples are given for six widely separated wells in Eastern and Western Canada whose locations are indicated in Figure 12.

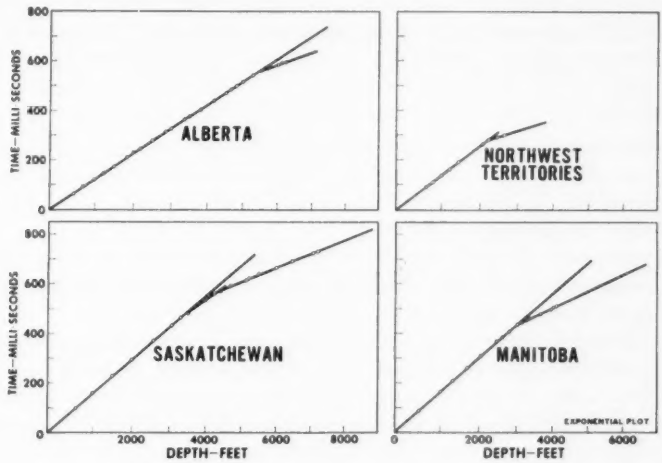

FIG. 13. Western Canada. Time plotted against depth raised to the power 0.91 using special exponential graph paper.

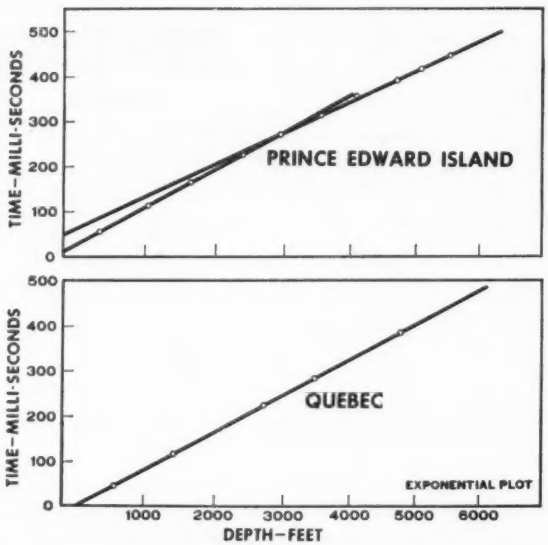

FIG. 14. Eastern Canada. Time plotted against depth raised to the power 0.91 using special exponential graph paper.

Figure 13 indicates the time depth curves of wells in Western Canada, plotted on exponential paper.

Figure 14 indicates the time depth curves of the wells in Eastern Canada, plotted on exponential paper.

THE USE OF EXPONENTIAL PAPER TO EXTRAPOLATE TIME DEPTH CURVES

Where intense velocity variation occurs laterally beneath the low velocity layer, the conventional correction is inadequate; since in the final result, the average velocity between datum and reflector remains variable, and gives rise to spurious time anomalies (Figure 15).

The spurious effects can be greatly minimized, however, by correcting accurately to a deep datum level, beneath which the effects of lateral variation in velocity are mild enough to be ignored (Figure 16).

Correction to datum levels several thousand ft below the surface requires considerable extension of the time depth curves, beyond the range of actual observation. A method for extrapolating these curves has been given in the section on the relationship between time depth curves at core holes. The procedure is rather awkward, however, and an improved technique will now be explained. It consists, as shown in Figure 17, of plotting time and depth on exponential paper.

A worthwhile refinement in this technique is shown in Figure 18. The time

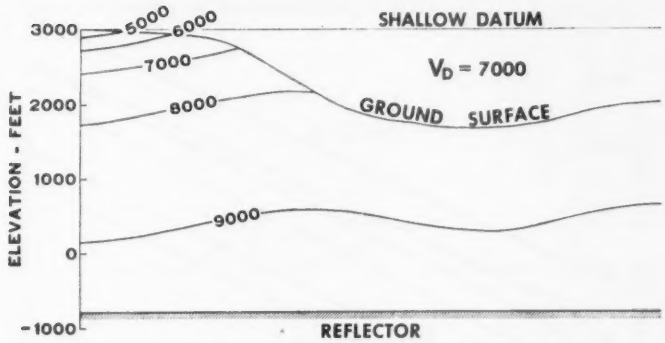

FIG. 15. Diagram to illustrate the inadequacy of conventional time corrections where intense lateral velocity variation occurs beneath the low velocity layer. Variation in average velocity between datum and reflector gives rise to spurious anomalies.

depth curves in Figure 17 project to depth in a variety of directions, and random error is introduced by slight variations in the slope that may be chosen for these straight lines. If, however, the time depth curves are referred to an isovelocity surface as origin of coordinates, instead of ground surface, the lines are parallel to each other, and a single slope may be assumed for them all. According to this technique the main error in correcting to deep datum levels lies in fixing the shallow isovelocity surface to be used as reference.

Correction Technique

Once the time depth curves are determined to depths required to reach the datum level, corrected values are obtained at core holes by computing the two-way time from surface to datum (taking into account the low velocity layer)

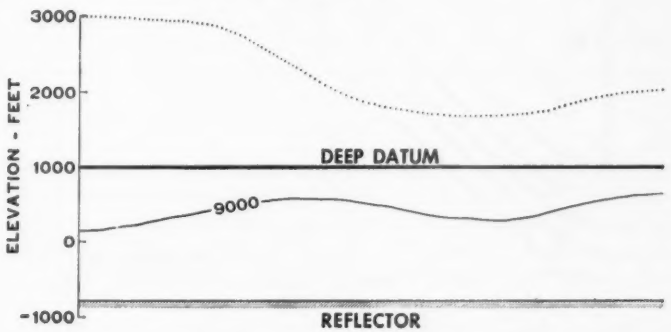

FIG. 16. Diagram to illustrate the use of a deep datum correction to minimize the effect of near surface velocity variations.

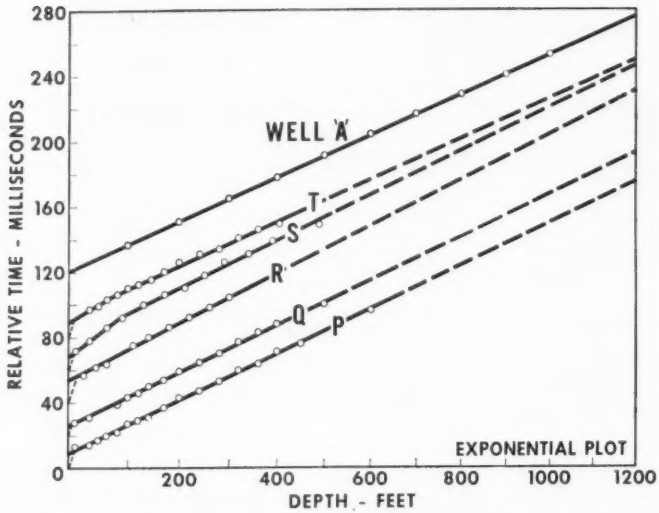

FIG. 17. Exponential plots of time depth curves—profile *PT*. Since the relationship between time and depth to the power 0.91 is linear, the curves are straight lines which may be extended.

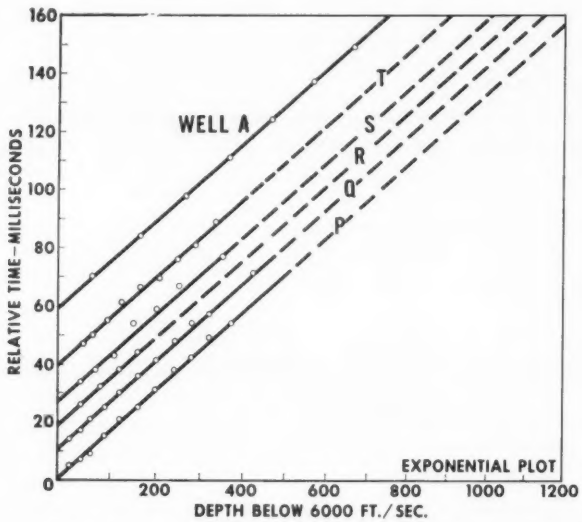

FIG. 18. Exponential plots of time depth curves—profile *PT* referred to the 6,000 ft/sec isovelocity surface as origin of coordinates. In this area, once a shallow isovelocity surface has been determined, a single time depth curve can be used to correct from it to datum.

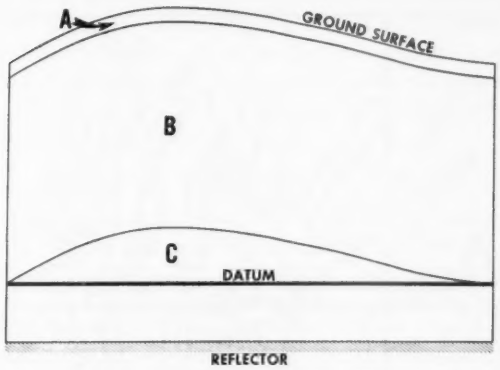

FIG. 19. Diagram to show the artificial zonation of the subsurface used for correction purposes between control points. Zone *A* is the first hundred feet; Zone *B* is the next 3,400 feet and Zone *C* is the rest of the section to a datum level 800 ft below sea level.

and subtracting it from the two-way time from surface to reflector. Results indicate two-way time between datum and reflector.

A modification of this technique was used to correct data between core hole surveys. For correction purposes, the subsurface was broken into three zones *A*, *B* and *C* (Figure 19).

Zone *A*, the first hundred ft below surface, was intended to include the low velocity layer; Zone *B* was the slab immediately below it, bounded above and below by surfaces parallel to the ground. In this area it was 3,400 ft thick. Zone *C* was the rest of the section to the datum plane, situated here 800 feet below sea level. Times through Zone *A* where known or could be determined accurately from uphole times; times through Zone *C* were approximated by assuming constant velocity, for at such depth any variation is minor. Times for Zone *B* were interpolated from time depth curves at control values by use of a very smooth contour map of the variation. Correction was the sum of the two-way times through Zones *A*, *B* and *C* subtracted from the two-way time from surface to reflector.

RESULTS

Figure 20 indicates the seismic map of the top of the Viking formation, corrected for lateral variation in velocity, above a datum level, 800 ft subsea.

The new map is not only free from evidence of topographic effects, but indicates several new features; among these is the prominent north-south ridge in the eastern part of the area, where reference to Figures 1 and 2 shows that both topography and the conventional map are predominantly low.

Imperial Oil Limited subsequently drilled three wells at *B*, *C* and *D*, to test this interpretation. Subsequently, competitors located wells at *E*, *F* and *G*.

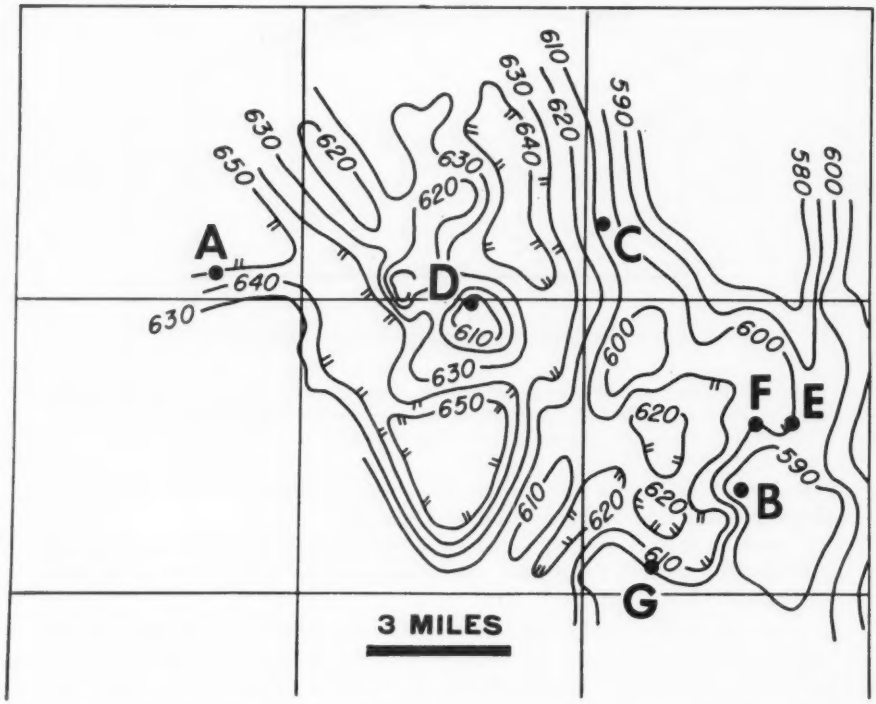

FIG. 20. Seismic map of the Viking formation corrected for lateral variation in velocity to a datum elevation 800 ft below sea level. A constant has been added to all values to facilitate comparison with Figure 1. Wells *B, C, D, E, F* and *G* were drilled after this map was made.

Taking well *B* as datum, elevations of the top of the Viking, in ft, predicted by old and new maps are compared with well markers (Table 7), to show the remarkable improvement achieved.

Application to Other Areas

Investigation of hundreds of surveys at core holes and wells in Western Canada shows that gross velocity variation in the Cretaceous section is effec-

TABLE 7

ELEVATION OF VIKING FORMATION, USING WELL *B* AS DATUM

	A	*C*	*D*	*E*	*F*	*G*
Original Map	+150	+ 75	+100	+50	+25	+200
Final Map	−300	−100	−100	−50	−50	− 60
Well Markers	−156	− 71	− 92	−13	−22	− 47

tively continuous below the weathering. Corrections for lateral variation in velocity can be made in all such areas, where the weathered layer presents no unusual problems. Four to five core holes per township are usually sufficient to correct to datum levels deep enough to minimize spurious effects due to lateral variation in velocity.

CONCLUSIONS

The assumption that vertical and lateral variation in velocity decreases with depth according to definite rules appears to be justified by the results. Correction to a deep datum, according to the assumptions used, minimizes the spurious anomalies without affecting those due to structure. Highs on the conventional map at *A* and *G*, that were proved spurious by later drilling, were eliminated from the corrected map; but the structural high at *B* was preserved. It is important to note that the spurious high at *G* does not conform to topography.

It does not matter whether the velocity effect is due to present overburden, to ancient overburden that no longer exists, to leaching by ground water action, or perhaps to combinations of these. This method of correction to a deep datum is applicable, provided only the isovelocity surfaces tend to conform to each other in local areas, and widen out at depth.

ACKNOWLEDGMENT

The writer wishes to express his thanks to Dr. R. W. Landes, Dr. D. C. Skeels, Mr. C. J. Chapman and fellow workers for their interest and pertinent comments, and to the Management of Imperial Oil Limited for permission to publish this material.

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GEOPHYSICS, VOL. XXIV, NO. 4 (OCTOBER, 1959), PP. 725–748, 11 FIGS.

BROADSIDE REFRACTION SHOOTING*

T. C. RICHARDS†

ABSTRACT

The three-dimensional refraction trajectories and travel times in seismic broadside refraction shooting across simple steeply dipping or faulted hypothetical structures are determined when the shotpoint is displaced from the axis. No curved surfaces are assumed and the diffractions to be expected from the structural discontinuities are evaluated. An approximate method for correcting arc time measurements taken over the opposite side to that of the shotpoint is investigated while the conversion of times to dip is discussed. Discussion is also given to the differences in the diffraction time curves caused by changing the shotpoint from the up to the down side of a fault and the relationship these curves have with the refraction time curves in both arc and broadside shooting.

The results of these studies indicate the care that should be taken in distinguishing between refracted and diffracted events, and in relating a measured broadside time to a particular point on the refractor. The latter may lead to significant error when simple mid-point depth computations, often resorted to in field work, are employed.

INTRODUCTION

The interpretation of the travel times in arc or broadside refraction shooting over buried geological structures such as anticlines or faults raises important difficulties unless good in line refraction control exists. In badly disturbed surface or sub-surface topography, adequate control is usually difficult to achieve and interpretation of the arc or broadside times has recourse to approximate methods.

In the early days of arc refraction shooting over anticlines, it was quickly recognized that if the shotpoint were located down flank, the minimum time along the arc would not be given where the arc crossed the axis but at a point displaced from the axis and over the remote flank; moreover, the slope of the arc-time curve over the remote flank would be less than that corresponding to its actual dip. This has been demonstrated by scaled model measurements and by theory applied to surfaces of revolution such as those of the cylinder, whose parameters were chosen to simulate known anticlines.

Two approximate methods of broadside interpretation are customarily used (a) "Offset" and (b) "Mid-point." The first is an attempt to refer the measured time to the point of emergence of the refracted path from the high-speed refractor while the second is an averaging process in which the average depth of the refractor between shotpoint and observation point (the distance between which is such that the refracted events appear late in the record) is assigned midway between these points. In both methods, migration of the depth points to allow for dip is applied.

It is instructive, however, to determine the accuracy of such methods in the case of simple steeply dipping or faulted hypothetical structures. This entails the determination of the ray trajectories and the arc or broadside time profiles

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and considering the reverse process of deriving structure from the time profiles. In this note we shall consider the anticlinal ridge, monocline and vertical fault, in which there are no curved surfaces.

In the strict sense, the term "refraction" when applied at critical angles of incidence is a misnomer, for here energy can only travel along the interface as a diffraction. However, in this paper the term diffraction will be reserved for those cases where an angular feature acts as a secondary source of energy.

THE ANTICLINCAL RIDGE

Consider an anticline with flanks dipping at angles of A and B as illustrated in Figure 1. The refracted path from a shotpoint, O, to an observation point, O', is $OQMQ'O'$, where OQ and $O'Q'$ are critical paths in planes normal to the flanks, and M is the point on the intersection of the two flanks through which the refracted wave passes. If P is the foot of the normal from O, then P, Q, and M

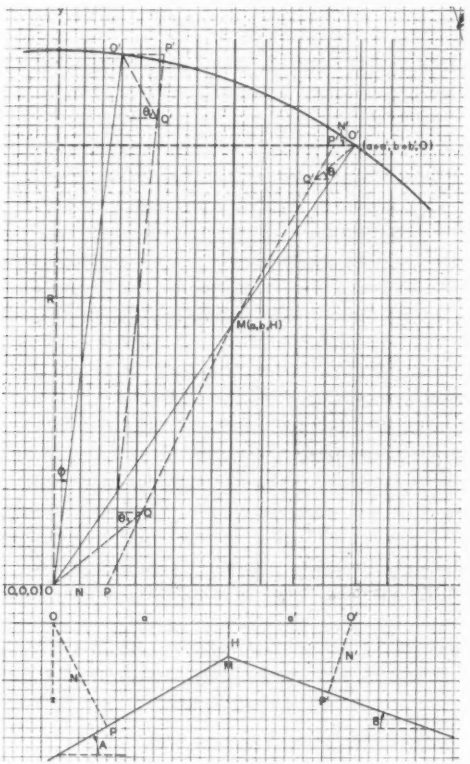

FIG. 1. Plan and elevation view of refraction paths from shotpoint to arc stations over ridge.

are co-linear and the plane of refraction is OPM: similarly on the remote flank, the plane of refraction is $O'P'M$.

Taking the shotpoint O, as the origin of rectanguar coordinates, the co-ordinates of other points in Figure 1 are:

$$\begin{aligned} &O' \ (a + a'), (b + b'), O \\ &P \ \ N \sin A, O, N \cos A \\ &M \ a, b, H = N \sec A - a \tan A \\ &P' \ (a - a' - N' \sin B), (b + b'), N' \cos B \end{aligned}$$

where N, N' are the lengths of the normals at O and O', and H is the depth to the ridge. The co-ordinates of Q, the point of entry in the flank may be shown to be given by

$$\begin{aligned} x &= N \sin A + \frac{a - N \sin A}{PM} \cdot N \tan \theta \\ y &= \frac{b}{PM} \cdot N \tan \theta \\ z &= N \cos A + \frac{H - N \cos A}{PM} \cdot N \tan \theta \end{aligned} \tag{1}$$

and of Q', the point of emergence, by

$$\begin{aligned} x' &= a + a' - N' \sin B - \frac{a' - N' \sin B}{P'M} N' \tan \theta \\ y' &= b + b' - \frac{b'}{P'M} \cdot N' \tan \theta \\ z' &= N' \cos B + \frac{H - N' \cos B}{P'M} \cdot N' \tan \theta \end{aligned} \tag{2}$$

where θ is the critical angle of refraction. In Figure 1, θ is shown as its plan view projection.

The lengths of the normals are given by

$$\begin{aligned} N &= a \sin A + H \cos A \\ N' &= a' \sin B + H \cos B \end{aligned} \tag{3}$$

and the surface travel distance, R, by

$$(OO')^2 = R^2 = (a - a')^2 + (b + b')^2. \tag{4}$$

Now the indirect path from O to O' is a minimum time path but as we will only consider those cases where the angles of refraction within the second medium are close to ninety degrees, it will be assumed that the path in the second medium

will lie along the interfaces, and given by QMQ'. It is quite reasonable to suppose that the energy travelling along this path—strictly diffracted energy—is greater than the truly refracted energy travelling along the straight line between points corresponding to Q and Q'. Of course, if the direction of observation subtends a large angle with the strike (which is avoided in practice), the foregoing energy supposition could be questionable.

It may be shown that the condition for minimum time is given when PM and $P'M'$ make equal angles with the line of intersection of the flanks, measured in the flanks; this condition is recognized to be that of the geodesic between P and P' and it may be written

$$\frac{b \cos A}{a - N \sin A} = \frac{b' \cos B}{a' - N' \sin B} . \tag{5}$$

Equations (3) (4) and (5) are sufficient to determine b, b' and N' provided the other quantities are known while the refraction travel time between O and O' is

$$T = (N + N') \frac{\cos \theta}{V_0} + \frac{PM + P'M}{V} \tag{6}$$

where V_0 and V are overburden and refractor velocities, respectively. The distances PM and $P'M$, may be determined from the co-ordinates of P, M and P'.

An important condition is that the offset distance $N \tan \theta$ and $N' \tan \theta$ must not exceed PM or $P'M$ respectively, or the vertical co-ordinates of Q and Q' must not be less than the depth, H, to the ridge. The appropriate values for a' may be found graphically since both $N' \tan \theta$ and $P'M$ vary linearly with a' to a first approximation.

For those refracted paths that do not pass over the ridge (see Figures 1 and 2) the geometry is much simplified and results in the well-known expression

$$T = \frac{R}{V} \cos \gamma + (2N - R \sin \gamma) \frac{\cos \theta}{V_0} \tag{7}$$

where $\sin \gamma = \sin A \sin \phi$ and

$$\sin \phi = \frac{a'}{R} .$$

In this case the limiting positions of Q and Q' may be shown to be given when

$$\begin{aligned} z_Q &= H = N \cos A(1 - \tan \gamma \tan \theta) \\ z_{Q'} &= H = N' \cos A(1 + \tan \gamma \tan \theta). \end{aligned} \tag{8}$$

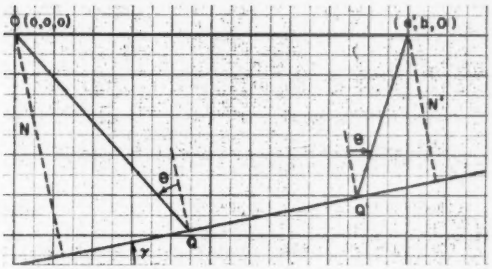

FIG. 2. Plane of refraction when path does not pass over ridge.

$$\sin \gamma = \sin A \sin \phi$$

$$\sin \phi = \frac{a'}{R}$$

$$Z_Q = N \cos A(1 - \tan \gamma \tan \theta)$$

$$Z_{Q'} = N' \cos A(1 + \tan \gamma \tan \theta)$$

DIFFRACTED ENERGY

It follows that in the interval between the observation stations corresponding to the limiting position on the shotpoint flank and the remote flank as defined above, there will be no arrival of refracted energy. The ridge top may be considered, however, to act as a source of diffracted energy which reaches the observation stations along varying paths. In practice, structures are flexed rather than angular so that there would be no limiting positions for the points of entry and emergence. An approximate theory to trace the path of refraction in the case of arc shooting over cylinders has been given by Germain-Jones (1951), but it is instructive to consider the diffractions from our hypothetical model and to see how their travel times may be related to those of the refracted paths.

In this case, the complete path is made up of a refracted path as far as the top of the ridge and diffractions to the observation stations, such that the total time is a minimum. Now the time taken along the path $OQMO'$ under consideration is

$$T = \frac{N \cos \theta}{V_0} + \frac{PM}{V} + \frac{MO'}{V_0} \tag{9}$$

and the minimum time condition may be shown to be given by

$$\sin \theta = \frac{\sqrt{b^2 + k^2 \sec^2 A}}{b} \cdot \frac{Y - b}{\sqrt{a'^2 + (Y - b)^2 + H^2}} \cdot \tag{10}$$

By assigning values to k, a', Y, H, V_0 and V, values of b to satisfy (10) may easily be found graphically since for angles near critical, it may be shown that b is approximately proportional to $\sin \theta$.

Writing

$$T - \frac{N \cos \theta}{V_0} = (T)$$

$$\frac{b}{PM} = \cos \phi$$

$$\frac{Y - b}{MO'} = \sin \theta'$$

and noting from (10) that

$$\sin \theta' = \sin \theta \cos \phi$$

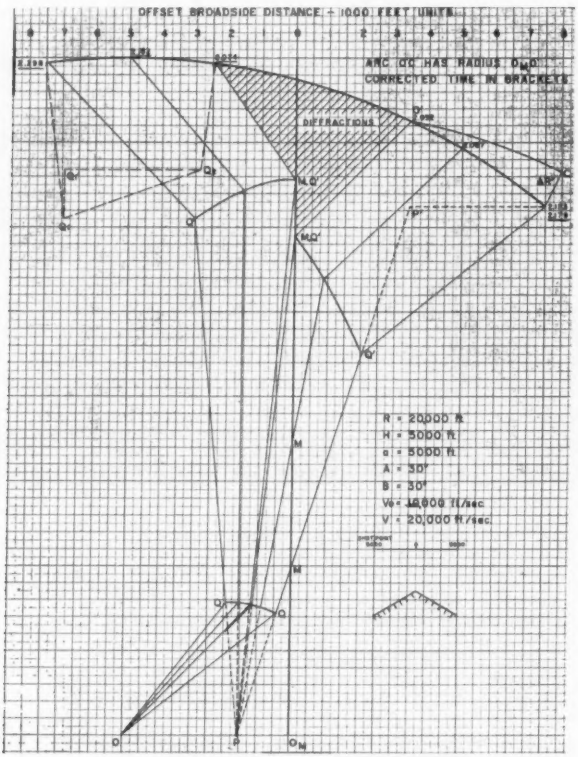

FIG. 3a. Plan view for ridge showing offset points from arc stations; constructions to give dip on shotpoint flank and time corrections for remote flank.

we obtain after substituting in (9)

$$(T) = \frac{b}{v \cos \phi} + \frac{Y - b}{V_0 \sin \theta \cos \phi} \tag{11}$$

$$= \frac{1}{V_0}\left[Y \frac{\sin \theta}{\cos \phi} + \frac{\sqrt{a'^2 + H^2}}{\sqrt{1 - \sin^2 \theta \cos^2 \phi}} \cdot \cos^2 \theta \right] \tag{12}$$

after manipulation.

In broadside observations Y remains constant and a plot of (T) or T against a', as to be expected, is symmetrical about the axis of the ridge. If arc observations are made, then Y is replaced by $\sqrt{R^2-(a-a')^2}$ and the time curve is asymmetrical.

THEORETICAL TIME CURVES

Figures 3a and 3b show in plan view the ray trajectories and travel times to be expected with a given set of parameters H, R, a, V_0 and V with $A = B = 30°$. The apparent dip as given by the time variations of the refracted arrivals is less on the remote flank than it is on the shotpoint flank while the diffraction zone is extensive. It should be noted that if the ridge be given a symmetrically curved top, then refractions would emanate from all points of its surface and the dashed curve in Figure 3b corresponding to diffractions constitutes, in effect, the limiting time profile when the curvature is infinite. Arrival times on this curve correspond to events which are relatively weak in energy on account of ray divergence. It is clear that by reciprocal shooting from the remote flank that a point midway between the two minimum time points will mark the true position of the ridge.

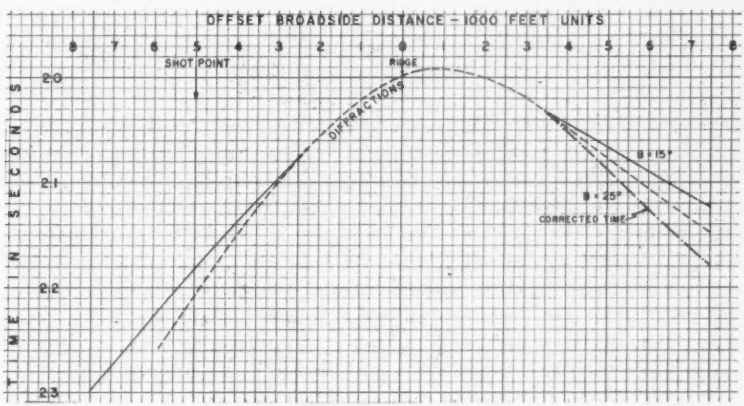

FIG. 3b. Time curve referring to Figure 3a.

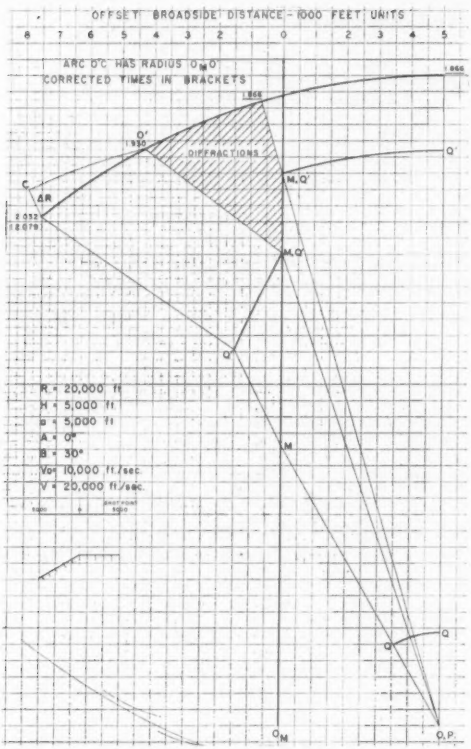

FIG. 4a. Monocline showing offset points when shotpoint is over horizontal section and time correction for dipping flank.

The distortion of the refracted time curve on the remote flank is largely due to the variations in the travel time in the refractor or in the second term in (6). The distortion gets less as anticlinal structures are replaced by quasi-synclincal structures, such as the case of $A=0$ and $B=-30°$ (discussed below in the section on the monocline). In the case of the ridge, an empirical time correction for distortion is obtained by drawing the arc $O'C$ from O_M as center and applying the correction $\Delta t=+\Delta R'/V$ where $\Delta R'$ is measured along O_MC (Figure 3a). This construction assumes that the axis of the ridge has been established and is based on the fact that if a shotpoint were located at O_M, the difference between times measured at O' and at C would be directly related to the dipping flank.

In regard to the assumption that the minimum time path travels over the surface of the ridge between Q and Q', it is pertinent to note that in the case of Figure 3a, the computed distance of $PM+P'M$ is 16,640 ft as against 16,400 ft

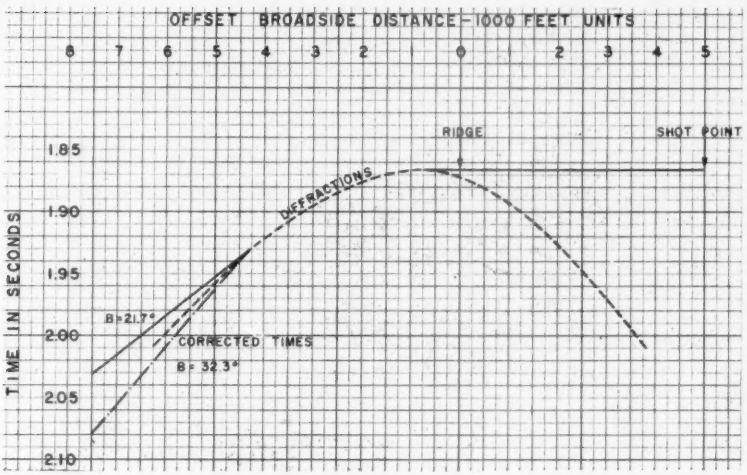

FIG. 4b. Time curve referring to Figure 4a.

for PP' when the observation point is at the rather large distance of 7,500 ft from the ridge. The corresponding time difference of about 0.01 sec is hardly significant. As previously stated, however, we believe the assumption is valid on energy concepts.

Corrected times should be referred to normals at the points of observation in computing the dip. This assumes that the flank has uniform dip without pitch which, of course, is actually the case. In practice, if the attitude of the flank beyond the locus of the offset positions $Q'Q'$ is uncertain, an approximate interpretation is made by offsetting back along the station radius a distance $N' \tan \theta$ and determining the vertical structural section by drawing the envelope to a series of arcs with varying radii, N'. Here, one value of N' is assumed and the others computed by adding algebraically the value $\Delta N' = \Delta t V_0 / \cos \theta$ where Δt is the difference in overall travel time to any other station. This may be sufficiently accurate for small dips, but large errors will arise otherwise. Thus, in Figure 4a, Q_1 and Q_2 are the surface offset positions corresponding to two stations on the arc over the shotpoint flank. If these points are used as centers for radii, N' and $N' + \Delta N'$, the envelope will give a skew dip section which bears no relation to the dip of 30°. A less erroneous result is obtained if Q_1Q_2 is projected on to a dip line as indicated and the arcs drawn with centers Q_1' and Q_2; the envelope will be found to give a dip of 40°.

By applying the correct formula

$$\tan A = \frac{\Delta t V_0}{\Delta a \cos \theta} \quad \text{or} \quad \tan B = \frac{\Delta t_c V_0}{\Delta a' \cos \theta}$$

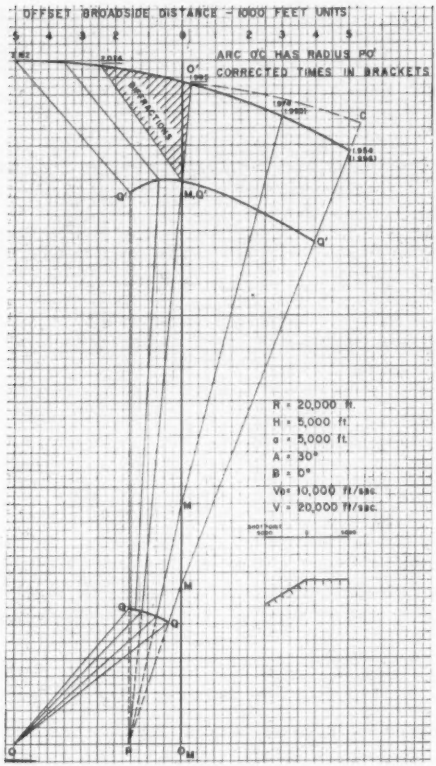

FIG. 5a. Monocline showing offset points when shotpoint is over rising flank and time correction for horizontal section.

we find that $A=30$ degrees and $B=25$ degrees. Consequently, if it is believed that pitch is a minor factor and dip is large, it is sufficiently accurate to refer normals to the points of observation which have been projected from the arc to a cross-strike line. The offset approach is one reserved as a refinement when other data are available, but great care should be exercised in attempting to compute the dip vector from the refractor offset points.

THE MONOCLINE

The governing equations for the monocline are simply derived from those for the anticlinal ridge by writing $A=0$ or $B=0$ and assigning negative angles to the dipping flank.

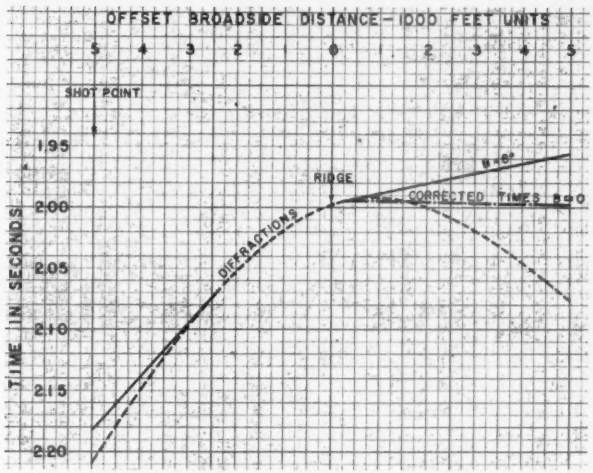

FIG. 5b. Time curve corresponding to Figure 4b.

Theoretical Time Curves

Figures 4 to 7 show the ray trajectories and travel times when $A=0°$, $B=30°$; $A=30°$, $B=0°$; $A=0°$, $B=-30°$; $A=-30°$, $B=0°$.

In Figure 4b, both refraction and diffraction times plotted against the arc station positions (offset to the broadside) are distorted and the apparent position of the top of the flank lies on the side remote from the shotpoint. From the zero gradient of time measurements over the shotpoint side, horizontal bedding may be inferred and the true position of the top of the flank obtained by offsetting the limiting refraction position with a time of 1.866 (Figure 4a) back along the radius, a distance $N \tan \theta$. The construction to obtain corrected refraction times is similar to that described in the case of the ridge.

Figures 5a and 5b refer to the same structure as in Figures 4a and 4b, but with the shotpoint over the steep flank. The diffraction time curve of Figure 5b is the reverse of that of Figure 4b, the average position of the minimum time point giving the true position of the top of the flank.

Figures 6a and 6b illustrate the situation in the case of horizontal bedding followed by a rising flank. Diffractions of the kind envisaged in Figures 4a and 5a do not arise, although where the two time curves of Figure 6b intersect, reinforcement of refracted energy may be expected. This is a diagnostic feature of refraction observations taken over synclines. Furthermore, there is no appreciable time correction for refractions over the rising flank. It is to be noted that the two time curves intersect at a point very close to the beginning of the rise and on the shotpoint side. If, however, refracted energy can be detected as second arrivals

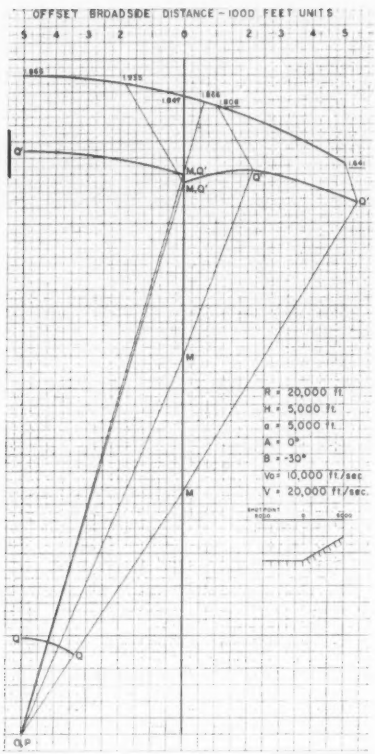

FIG. 6a. Monocline showing offset points when shotpoint is over horizontal section and observations carried over rising flank.

as far as the theoretical limits corresponding to the two values of MQ' in Figure 6a, calculation from their observed times should fix the position of the beginning of the rise with a good degree of accuracy.

Figures 7a and 7b show the geometry and offset broadside times when the previous structure is shot from the opposite side. There is little time distortion over the remote flank while the point of intersection of the two refracted time segments is appreciably displaced from the ridge and on the remote side. As before, calculation from the limiting times should mark the beginning of the rise with good accuracy.

THE VERTICAL FAULT

In the case of the vertical fault, the bedding on both sides of the fault will be considered as horizontal and the geometry determined when the shotpoints are

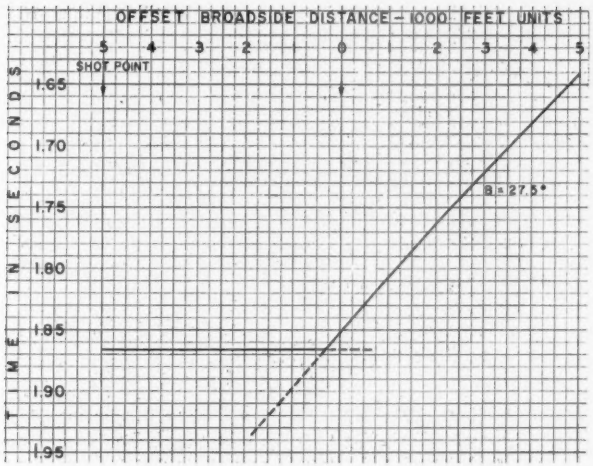

FIG. 6b. Time curve corresponding to Figure 6a.

located (a) on the down side, and (b) on the up side—not too distant from the fault. Observations are made along the arc of a circle, or along a broadside.

Shotpoint on Downside

Figure 8a illustrates the travel path from the shotpoint O to the observation station O' in case (a). The plane of refraction normal to the bedding is vertical and the travel time is given by

$$T = \frac{OQ}{V_0} + \frac{QM}{V} + \frac{MQ'}{V} + \frac{Q'O'}{V_0}$$
$$= \frac{r}{V} + \frac{(H + h)\cos\theta}{V_0} + i_x \tag{13}$$

in which MQ' is a quasi-refracted path from M.

Since the path $MQ'O'$ is a minimum time path, Snells law applies and, therefore, $\sin\beta = V_0 \sin\alpha / V$.

If varying angles from zero upwards are now assigned to α, β may readily be computed and hence x, since

$$x = h\tan\alpha + H\tan\beta. \tag{14}$$

In the case of arc shooting, r follows since

$$r = R - x$$

and (13) may then be computed for T. The corresponding observation distance,

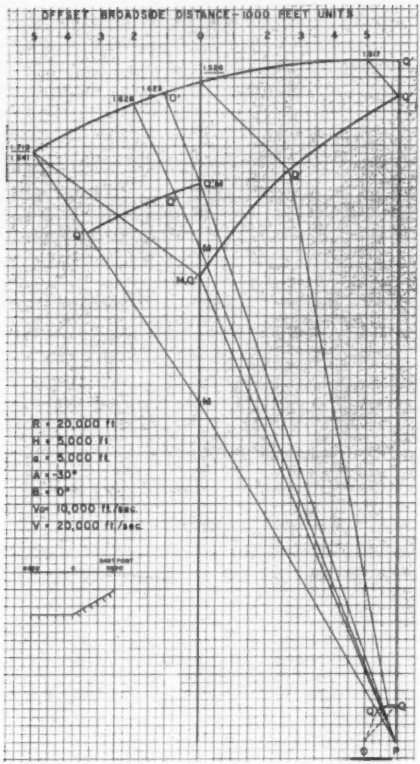

FIG. 7a. Monocline showing offset points when shotpoint is over dipping flank and observations carried over horizontal section.

a', measured from the fault edge is given by

$$a' = a(R/r - 1).$$

In the case of broadside shooting, Y is constant and

$$r = (Y/\cos\phi) - x$$

where

$$\sin\phi = a/r.$$

By assigning increasing values to ϕ, varying values of r (and hence x) may be determined and, subsequently, the appropriate values of α and β from (14).

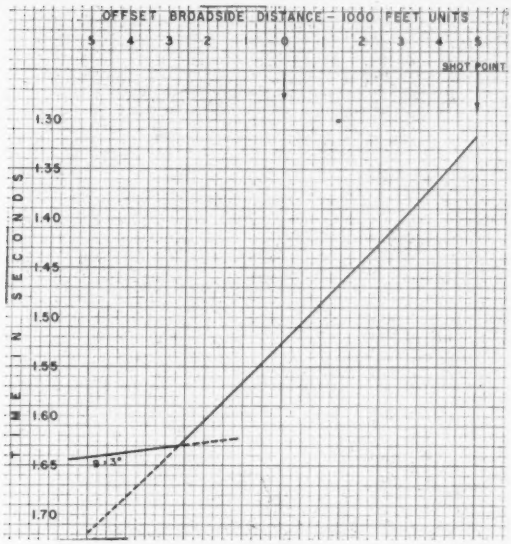

FIG. 7b. Time curve corresponding to Figure 7a.

Diffracted Energy

The fault edge may be expected to act as a secondary source for the transfer of energy along the refractor on the upside as indicated by the path $OM'Q_D'O_D'$ in Figures 8a and 8b. The travel time along this path is

$$T = \frac{\sqrt{a^2 + b^2 + H^2}}{V_0} + \frac{H \cos \theta}{V_0} + \frac{\sqrt{a'^2 + (Y - b)^2}}{V} \tag{15}$$

and for minimum time

$$\sin \theta = \frac{\sqrt{a'^2 + (Y - b)^2}}{Y - b} \cdot \frac{b}{\sqrt{a^2 + b^2 + H^2}} \cdot \tag{16}$$

This expression for sin θ bears a reciprocal relation to (10) as the energy from the shotpoint travels to the diffracting edge directly through the overburden before travelling along the refractor on the upside, as opposed to a refraction path on the shotpoint side before diffraction, in the case of the dipping flank. Travel times for various values of a' may be computed as previously indicated for the anticlinal ridge.

In the case of observations made on the same side as the shotpoint, energy along the path $OM_1'M_2'O_D''$ (Figure 8b) would be vanishingly small unless the

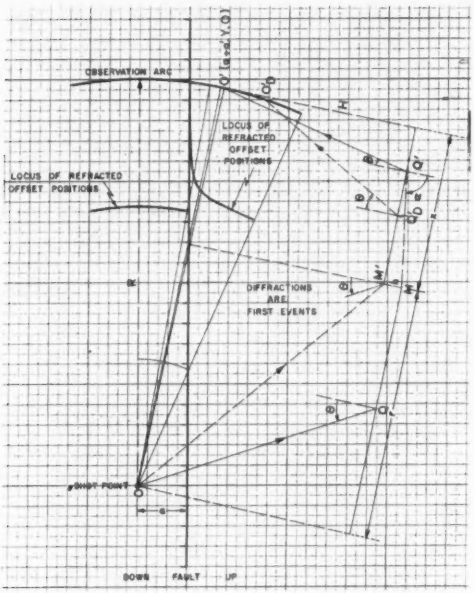

FIG. 8a. Plan and elevation view of refractions and diffractions across fault; shotpoint on downside.

fault edge were rounded, in which case the travel time along the path would be given by

$$T = \frac{Y}{V} + \left[\sqrt{(a^2 + H^2)} + \sqrt{(a'^2 + H^2)}\right] \frac{\cos\theta}{V_0}. \tag{17}$$

The refracted event with the time of (17) may arrive earlier or later than the refraction on the same side as the shotpoint, depending on a, a', H and h. For equality in time and in the case of broadside shooting or when $r \simeq Y$, it may be shown that

$$2(H + h) = \sqrt{a^2 + H^2} + \sqrt{a'^2 + H^2} \tag{18}$$

which is independent of the velocities V and V_0. Theoretically, (18) provides a check on the throw of the fault which has been determined otherwise. Figures 10a and 10b indicate that diffracted travel times are asymmetrical about the fault edge whether arc or broadside observations are made.

Shot Point on Upside

The geometry of shooting from the upside is illustrated in Figure 9. Deter-

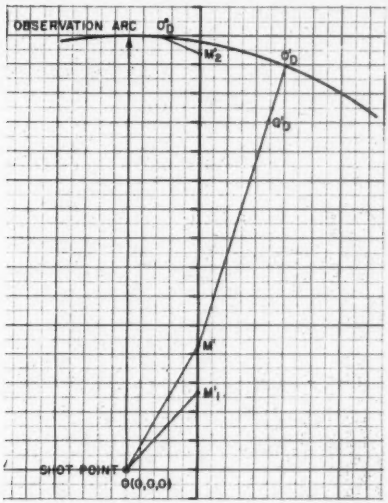

FIG. 8b. Refractions from fault edge of Figure 8a.

mination of the refracted and diffracted travel times follows a similar (but reversed) procedure as in the case of shooting from the downside.

In this case, however, diffracted times are symmetrical about the fault when V is constant but not when arc observations are made, as illustrated in Figures 10a and 10b.

Shotpoint over Fault

It is of interest to consider the general equation (12) when the shotpoint lies over the fault or when $\phi=0$. Ve then have

$$(T) = \frac{1}{V_0}\left[V \sin\theta + \sqrt{a'^2 + H^2}\cos\theta\right]. \tag{19}$$

Writing

$$(T)' = (T) - \frac{V \sin\theta}{V_0}$$

we derive

$$(T)'^2 = (T)_0'^2 + a'^2\frac{\cos^2\theta}{V_0^2} \tag{20}$$

where $(T)_0'$ refers to the value of T' at $a'=0$. Equation (20) represents a hyperbola whose asymptotes have a slope of $\cos\theta/V_0$, and has been given previously

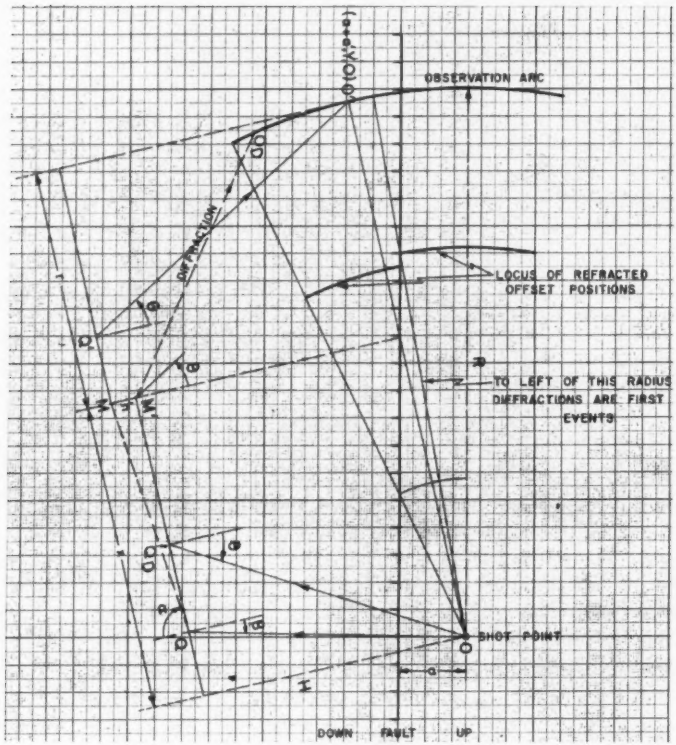

FIG. 9. Same as 8a but shotpoint on upside.

by Ledoux (1957). In his paper, Ledoux draws attention to the fact that this slope is cos θ times that obtained when considering inline shooting across a fault. This inline condition may be derived from (12) by putting $\phi=90°$ and noting that $V/\cos\phi$ with this condition as determined from the steps leading to (11) is given by $a+\sin\theta(a'^2+H^2)^{1/2}$.

In order to determine the function $\cos\theta/V_0$ from the measured times T and distances a', we proceed as follows:

Putting

$$D = T - \frac{V}{V} = \sqrt{a'^2 + H^2}\,\frac{\cos\theta}{V_0} + \frac{H\cos\theta}{V_0} \tag{21}$$

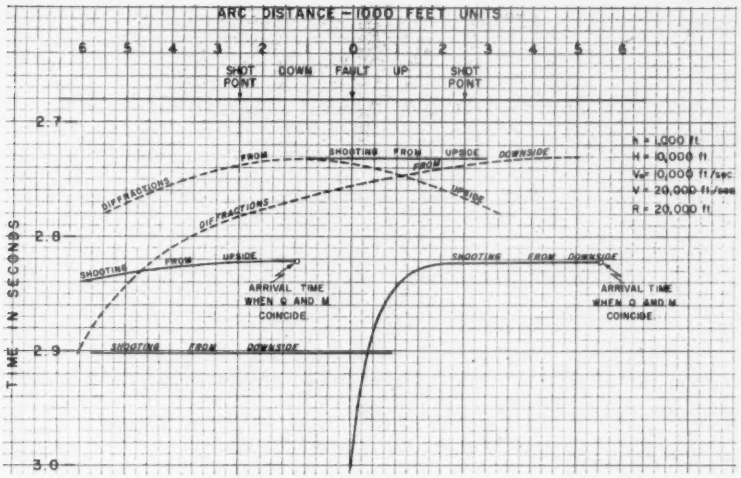

FIG. 10a. Time-Arc distance curves referring to Figures 8a and 9.

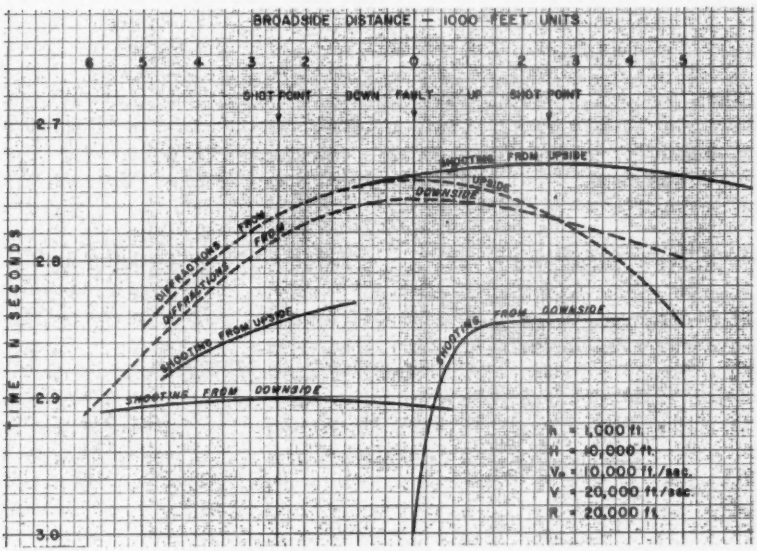

FIG. 10b. Time-broadside distance curves referring to Figures 8a and 9.

we have

$$D_0 = \frac{2H \cos\theta}{V_0}$$

which gives on substitution in (21)

$$\left(D - \frac{D_0}{2}\right)^2 = (a'^2 + H^2)\frac{\cos^2\theta}{V_0^2}$$

or

$$D(D - D_0) = \frac{a'^2 \cos^2\theta}{V_0^2}. \tag{22}$$

Therefore, the slope of the straight line obtained by plotting $(T - Y/V)\Delta T$ by a'^2 gives the square of the required function.

Theoretical Time Curves

Figures 10a and 10b show the arc and broadside (Y = constant) refraction and diffraction time curves to be expected over a fault with throw of 1,000 ft, a depth of 10,000 ft, arc or broadside distance 20,000 ft, and a shotpoint displacement from the fault of 2,500 ft. In Figure 11a, and shooting from the downside, refraction arrivals give a steepening time gradient as the fault is approached ($\alpha \rightarrow 0$) and the energy content of these arrivals may be expected to decrease in the same direction; the first detectable events would be those corresponding to that part of the time curve whose time gradient is near zero. The throw of the fault as determined from the time interval of 0.08 second is 920 ft which is less than the true value. If the limiting position of refracted arrivals from the downside (at a distance of 900 ft from the fault edge) is clear, then the position of the fault edge is easily determined by offsetting towards the shotpoint by a distance $H \tan\theta$. The diffracted events show steadily decreasing times from the downside to the upside and if such events were observed in practice, then times should be examined to see whether they could substantiate the features determined from the refraction results.

In the case of shooting from the upside, the upper time segment should furnish the position of the fault edge while the lower time segment corresponding to the downside should be characterized by strong energy at its limiting position ($Q' = M$) and this energy should decrease at increasing distances from the fault, corresponding to decreasing angles, α. The throw of the fault, if determined from the minimum time interval of 0.09 sec between the upper and lower segments is 1,040 ft or greater than the true value. Ideally, an averaging of the two computed fault throws from the two positions of the shotpoint will lead to an improved result. The times of the diffracted events exhibit the normal hyperbolic diffraction characteristic although distorted; the minimum time point is dis-

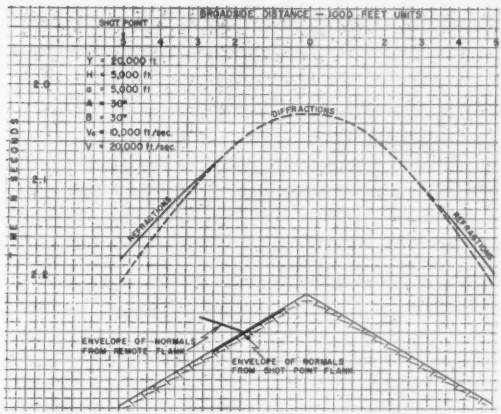

FIG. 11a. "Mid-Point" interpretation of Figure 3b.

placed as indicated. As before, the form of this time curve should be examined to check the results established by refraction.

Figure 10b which shows times plotted by actual broadside distances where V remains constant, portrays the time effects of increasing horizontal travel distances; these effects are, of course, corrected to arc times before considering their corresponding delay times. The downside diffraction curve is still asymmetrical, but by virtue of the geometry when shooting from the upside, the upside diffraction curve is symmetrical about the fault edge. It is pertinent to see how nearly this symmetrical curve yields the function $\cos \theta / V_0$ if the relation (22), which strictly refers to the case of a shotpoint over the fault, is applied. We

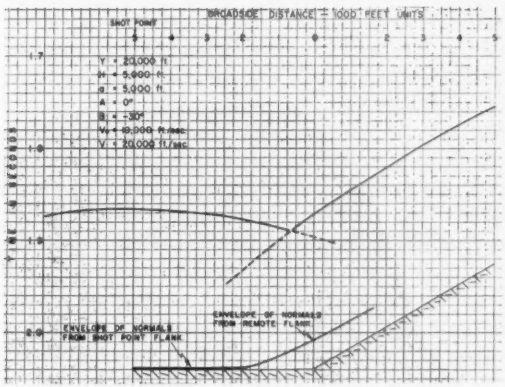
BROADSIDE DISTANCE = 1000 FEET UNITS
SHOT POINT
Y = 20,000 ft
H = 5,000 ft
a = 5,000 ft
A = 0°
B = -30°
V0 = 10,000 ft/sec
V = 20,000 ft/sec
TIME IN SECONDS
ENVELOPE OF NORMALS FROM SHOT POINT FLANK
ENVELOPE OF NORMALS FROM REMOTE FLANK

FIG. 11b. "Mid-Point" interpretation of Figure 6b.

find that whereas $\cos \theta/V_0$ at $a=0$ is 0.866×10^{-4}, the value at $a=2{,}500$ ft is 0.873×10^{-4}; an additional set of calculations for $a=5{,}000$ ft yields 0.887×10^{-4}. At this value of shotpoint displacement from the fault and with the other selected parameters, an error of only about $+2$ percent is entailed, and this would lie well within experimental error.

In regard to the diffraction time curve obtained when shooting from the downside of the fault and when observations are made over the downside, Figure 10b shows that equality of time with the refraction time segment, obtained under the same conditions, is given some 6,000 ft away from the fault and this is in accordance with expression (18).

THE INCLINED OVERTHRUST BLOCK

The geometry in this case is similar to that of the anticlinal ridge as far as the ridge and when the shotpoint lies over the block. If the shotpoint lies over the downthrown or subthrust side, the geometry becomes more involved and depends on the velocity of the material between the two units. If the material is relatively thick and possesses comparatively low velocity, it would be advisable to consider the subthrust unit as a separate problem, but if the velocity is not sensibly different from that of the two high-speed units, the problem involves the dipping flank and vertical fault theories discussed above.

MID-POINT INTERPRETATION

It can readily be seen from a study of the various arc or broadside time curves illustrated above that mid-point interpretations of observations made across structures defined by relatively steep dip or faulting may lead to serious errors in computed depths. Thus, in Figures 10a or 10b, the average depths, determined from the times of those segments of the refraction time curve belonging to arrivals on the side of the fault remote from the shotpoint, would be such as to infer a fault throw of about one half of its true value. Two other cases are considered and illustrated in Figures 11a and 11b. Here the anticlinal ridge with $A=B=30°$ and the monocline with $A=0$, $B=-30°$ are considered. Computed times are those when V is constant. In both, the travel times, compared with the arc times, are increased by virtue of the increasing horizontal distances from shotpoint to geophone but, in the case of the ridge, it is to be noted that the refraction time segments are approximately symmetrical with respect to the ridge. Distortion on the flank remote from the shotpoint is very small and this is due to the fact that the distances, PP', between the feet of the normals, only vary by small amounts. (The diffractions are, of course, symmetrical about the ridge.) However, in interpretation, measured times should first be corrected for differences in horizontal travel distances and then by the artifice described above.

The mid-point interpretation, obtained by assigning half the total delay time midway between shotpoint and geophone, converting these times to normal depths and constructing their envelope yields two structural segments: one on

the shotpoint flank as far as the limiting position of refractions and a second segment, quite unrelated in position or depth, although possessing the relevant dip.

In Figure 11b, the decreasing refraction times over the rising flank are greatly influenced by differences in PP' so that a broadside interpretation would require a correction for variations in the horizontal travel distance. The mid-point interpretation of the first events shows this flank with the correct dip, but with appreciable displacement towards the shotpoint.

The above examples show the weakness of mid-point interpretation when structural relief cannot be considered as small. In practice, the drawing of normals to obtain the envelope, frequently results in confusion and this is doubtless due to structural anomalies of small lateral extent but sharp relief. An interpretation which relates the measured time differences, corrected for travel distance, to differences in the normal depths along the broadside itself or its offset back towards the shotpoint, should result in reasonable agreement with actuality. Weak events that may appear to bridge strong events on a record should be suspected as diffractions and their times considered in the light of the appropriate theory.

GENERAL OBSERVATIONS

The solution of the governing equations in the theoretical structures considered above is laborious by conventional mathematical methods but is rendered speedy by digital computing machines. Several check solutions of the problems related to the anticlinal ridge or monocline treated in this paper as well as other solutions for varying parametric changes have been determined using the Almac III E Digital Computer. In setting up the problem, ten general steps are coded and fed into the computer. By applying discrete values for a, A, B, H, V, V_0, R and a', the computer comes out with a solution for T in about one minute. In determining the limiting value of a', when $N' \tan \theta = P'M$, the shrinking average procedure is adopted but if a' is expected to be negative, this information must be fed into the machine as an extra step.

As is often the case, seismic theory meets with difficulties when applied to practical measurements, especially in zones of appreciable tectonic disturbance. Velocity changes within both the refractor and its overburden and varying thickness of the refractor may contribute importantly to the energy content of the refracted wave. Diffracted events may be set up at any discontinuity and although the energy in such events may be relatively small, their identification should be checked from their characteristic time-distance relationship which is easily determined knowing the depth of the diffracting edge. This relationship for a deep source, however, yields a curve with small curvature which may not easily be distinguished from the trace of refracted events from a refractor with small dip. The effects of a disturbed overburden which normally accompany thrusting are often visible on a record and lead to interference of the second or later events which are expected to identify the refractor.

It is important to be able to visualize the refraction or diffraction trajectories in and out of structures of various forms and the general equations established above should help the seismic interpreter to this end; the structures chosen in the cases of the anticline and monocline have been given large dips for ease of illustration. An extension of the investigations by systematically changing the several variables should be most informative and provide a set of rules, albeit qualitative, which should also lead to a better understanding of broadside refraction problems.

Broadside or arc reconnaissance observations are indispensable in detecting steeply dipping and faulted limestone structures such as those in the Rocky Mountain foothills of Western Canada. Inline observations across such features are less informative and, as is well known, have no significance when observing down flank whose dip is equal to the critical angle. The inline should be restricted to the direction of the regional strike and away from the disturbed zone.

In some recent investigations into the nature of the refracted second event we have found that this event carries much less energy than the wide-angle reflection which follows at a later time at distances greater than critical. A good example is given by Richards and Walker (1959) and, unless good quality records are obtained, a prominent second event could be mistakenly identified as a refraction. This is not important if depth determinations are made from the times of events recorded near the critical distance but this is rarely possible in practice, and the inline time distance curves for the second event should be examined in the light of reflection theory. A detailed study of the identification of the second event will be the subject of a future paper.

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GEOPHYSICS, VOL. XXIV, NO. 4 (OCTOBER, 1959), PP. 749-760, 8 FIGS.

SUB-BOTTOM DEPTH RECORDER*

WALTER C. BECKMANN,† ARCHIE C. ROBERTS,† AND BERNARD LUSKIN†

ABSTRACT

The Sub-bottom Depth Recorder (SDR) has been developed to study the underlying geologic structure of water covered areas. The SDR is essentially a broad-band, high-powered echo sounder which utilizes one of two sound sources.

The first, an electrical spark discharge (Sparker), has produced penetrations in excess of 600 ft in 50 ft of water. The second, a combustion chamber using a mixture of propane and oxygen (RASS), has produced penetrations in excess of 1,400 ft in 80 ft of water.

Results obtained from the SDR have been found to be in excellent agreement with test boring and seismic refraction data.

INTRODUCTION

Since the summer of 1957 an active program has been underway at the Lamont Geological Observation directed toward the study of sub-bottom structures underlying water-covered areas through the use of high-powered echo sounders. Emphasis has been placed on the use of broad-band, low-frequency sources to produce the necessary acoustic energy.

The present Sub-bottom Depth Recorder (SDR) utilizes as a sound source an electric spark discharge (Sparker) or the combustion of a mixture of propane and oxygen in a small chamber (RASS). The SDR is constructed so that one may choose the particular source best suited to the area and structure under survey. One can further select the passband of the receiving circuit to provide an optimum signal-to-noise ratio.

A number of equipments designed to obtain sub-bottom echoes have been reported in the literature (McClure, Nelson, and Huckaby, 1958; Smith, 1958; and Padburg, 1958). Each of these has used rather large crystal or magnetostrictive transducers. The trend has been to utilize lower frequencies, of the order of 1–9 kc, in order to achieve more penetration. This has resulted in rather large equipments, particularly the transducer sections. Hence, the portability is limited, and installation is time-consuming and involves rather expensive modifications to the ship's hull.

Of the two sources available with the SDR, the electric spark discharge is the more common. It has been used for studies of underwater sound propagation by Anderson (1953), among others, and has been applied to the study of sub-bottom structures with notable success by members of the Woods Hole Oceanographic Institute, Knott and Hersey (1956), and Hersey[1] to the study of sub-bottom

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[1] Personal communication.

structures. A simplified spark discharge has been used by Press and Oliver (1955), and Hall (1956), among others.

The combustible gas sound source, called the RASS for Repeatable Acoustic-Seismic Source, is a newer concept and has not been reported in the literature, to our knowledge. Single shot, non-repeatable gas sound sources have been reported in patents by McCollum (1951) and Merten (1955), but these have been rather large, complex machines not suited for a continuously operating, shipboard sound source.

The Sparker is used primarily when emphasis is to be placed on the study of relatively shallow, complex sub-bottom structures. The acoustic signal produced contains significant energy between 300 and 5,000 cps. The use of these frequencies (considered here to be high) permits excellent definition of small gradients or changes in sub-bottom sediments. A record made using the Sparker in Long Island Sound is shown in Figure 1. Penetrations in excess of 600 ft in 50 ft of water have been recorded.

The RASS is used when more energy is required in order to study deeper layering. The fundamental frequency of the RASS is 35 cps; the signal includes this frequency and the harmonics above. Frequencies up to 3,000 cps are used to record the sub-bottom reflections. A record made with the RASS in Long Island Sound is shown in Figure 2. Penetrations in excess of 1,400 ft in 80 ft of water have been made. Here the geologic structure has been the limiting factor; a probable limit of the instrument is 2,000 ft in coastal plain sediments.

Geologic surveys have been made using the SDR in Long Island, Block Island, and Rhode Island Sounds, Chesapeake Bay, the Red Sea, the Beagle Channel (Cape Horn), and on the Atlantic Coastal Plain. A distance of some 3,000 miles has been covered and has given valuable data of the areas involved.

DESCRIPTION OF EQUIPMENT

The equipment consists of two parts, the transmitting section and the recording section. The transmitting section consists of a choice of either the Sparker or the RASS sound sources (see Figure 3).

An electro-chemical type recorder provides a synchronized trigger pulse corresponding to a writing stylus position at the left of the recording paper. In the case of the Sparker, this triggering pulse switches a capacitor charged to 8,000 volts across the Spark Electrode Assembly shown in Figure 4. The spark discharge from the center electrode to the concentric ring produces a loud, short-duration sound. The electrode is towed directly in the water by the electrical connecting cable. In the case of the RASS, the triggering pulse energizes a spark coil producing an ignition spark in the combustion chamber to which propane and oxygen are continuously fed (see Figure 5). The combustion chamber is towed in the water in a small paravane at a depth of 2 to 5 ft.

A receiving hydrophone encased in a hose is towed behind the ship. The reflected signal detected by the hydrophone is pre-amplified, passed through a vari-

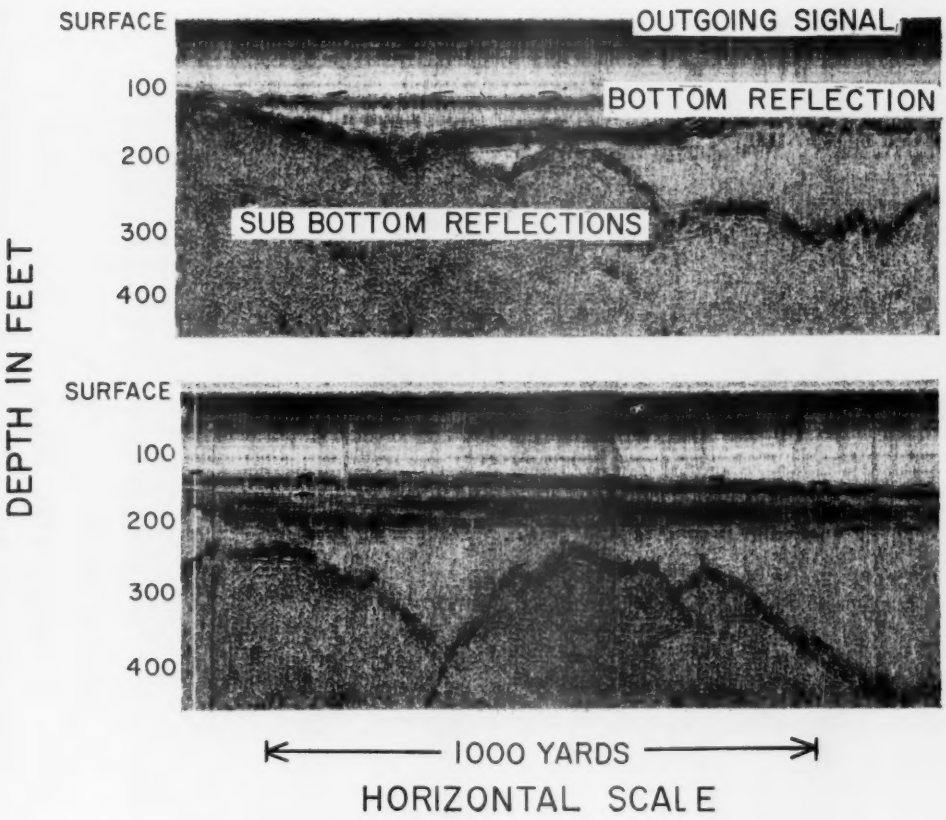

FIG. 1. A portion of a SDR record made in Long Island Sound using the Sparker sound source. The top of the record corresponds to the water surface, the first reflection to the water bottom, and the successive reflections to the various sub-bottom horizons. These later events correspond to an intermediate horizon presumed to be the interface between the Recent and Pleistocene deposits and to the underlying bedrock.

able passive filter, then amplified and printed on the recorder. A time variable gain (TVG) print amplifier is used so as to permit one to see clearly the deeper horizons without blacking out the shallow, and hence stronger, arrivals. The TVG is controlled by the trigger pulse from the recorder, once per second.

A recorder stylus traverses the width of the recording paper in one second, giving a depth of 400 fathoms (2,400 ft) across the paper, for a velocity of 4,800 ft/sec. The repetition rate of the Sparker can be made four, three, two, or one per second by utilizing auxiliary trigger pulse contacts. That is, several records

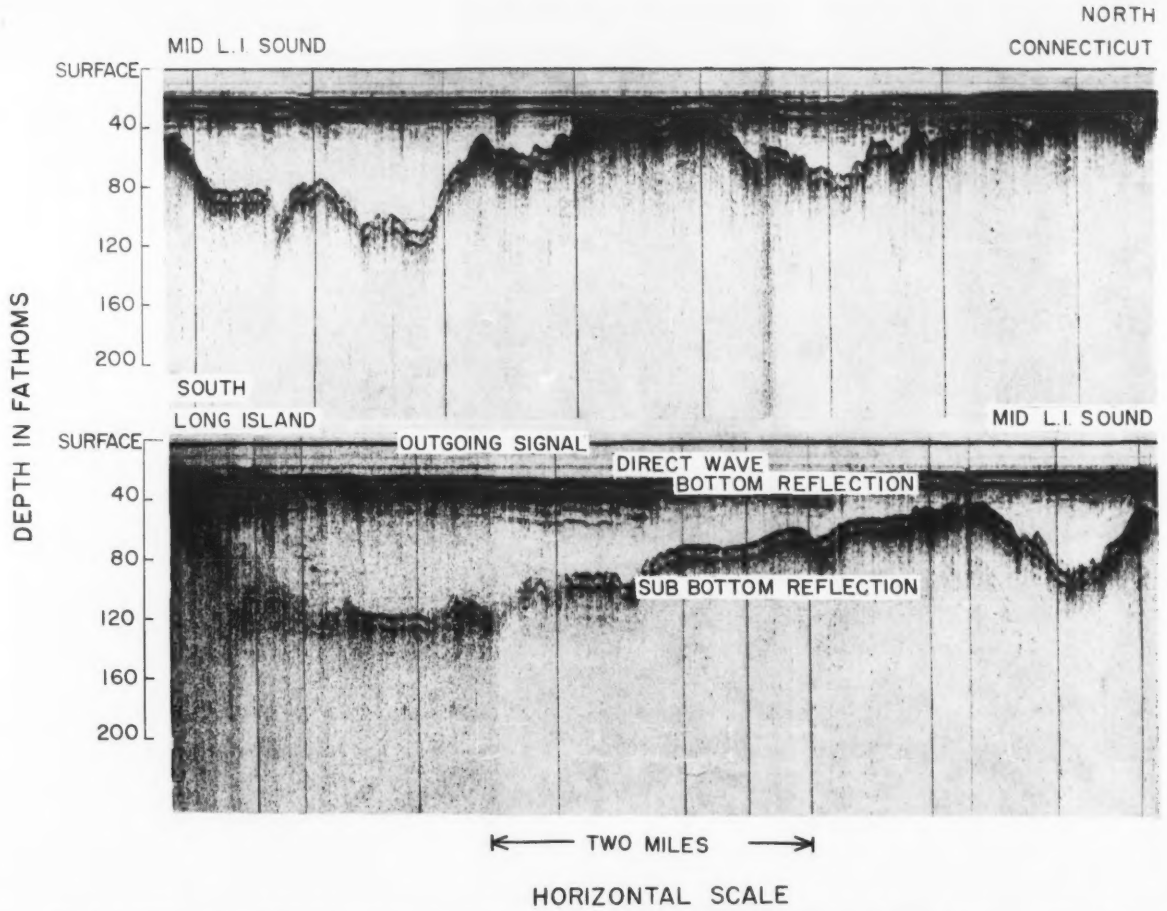

FIG. 2. A portion of a SDR record made in Long Island Sound using the RASS sound source. Because of a separation between the RASS and the receiving hydrophone, the direct sound-path arrival is present. Succeeding reflections are the water bottom and bedrock. Some intermediate horizons are shown, although not clearly. The double character of the reflections is a result of the fundamental frequency of the RASS signal. The

can be made across the paper having depth scales which are divisions of 400 fathoms (2,400 ft).

In the case of the record shown in Figure 6, a repetition rate of three per second was used to give three records each having a total depth scale of 800 ft. The use of TVG permits one to obtain several complete records at increasing gain on the same record paper. It has been found that this system is more satisfactory than a single TVG record, the reason being that shifting depth scale from 100, to 200, · · ·, to 400 fathoms can be done simply by selection of the repetition rate of the trigger pulse and does not involve speed changes of styli or paper transport. In addition, it provides a greater time-variable gain range for each reflection horizon.

The repetition rate of the RASS can be made two or one per second giving depth scales of 200 or 400 fathoms. Much of the thinking behind this recording scheme has been influenced by work in the Long Island area where the deepest reflecting horizon (bedrock) slopes gently from Connecticut to the south southeast. A typical survey line then was begun by the Sparker at four per second and then switching to the RASS at two per second as the bedrock deepened. The

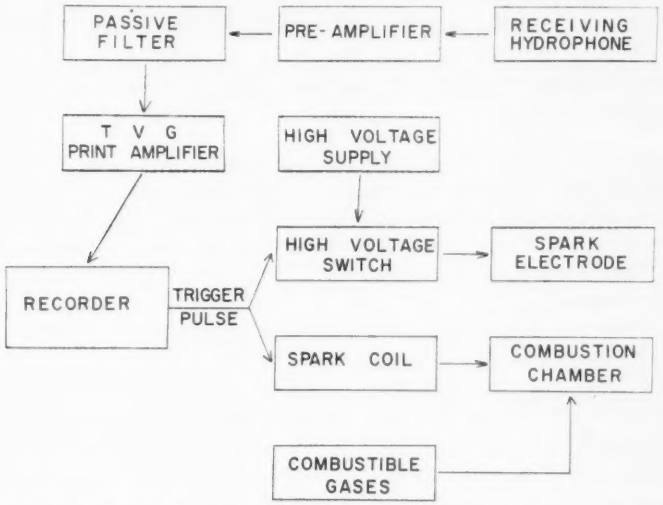

FIG. 3. A block diagram of the SDR equipment. The recorder provides the synchronized trigger pulse which in the case of the Sparker operates a switch which places a charged capacitor across the spark electrode producing the sound, in the case of the RASS the trigger pulse pulses a spark coil which provides the ignition spark in the combustion chamber which is continuously fed propane and oxygen.

The reflected sound is detected by the receiving hydrophone, the signal is then pre-amplified, filtered, amplified, and printed by styli on a moving belt on an electro-chemical recorder.

FIG. 4. The Sparker electrode assembly. The sound-producing spark discharge is between the center electrode and the concentric ring. This replaceable portion of this unit wears out in from 6 to 9 hours and must be replaced.

SDR is equipped so that the change from one sound source to another or from one repetition rate to another requires only a few seconds.

Power consumption for the SDR varies, of course, depending on which sound source is used. The SDR with the Sparker requires about 1,200 w of 110 volts ac power. This power may be unregulated like that produced by a small 2-kw gasoline generator. The SDR with the RASS requires only about 350 of 110 volts ac electrical power plus propane and oxygen supplies. At a repetition rate of one per second the hourly gas consumption is 30 ft^3 of oxygen and about one pound of liquid propane. More simply, a standard 300 ft^3 hand-carried tank of oxygen is required for each 10 hours of continuous operation. A large tank of propane such as that used for home cooking (150–200 lb) will last for 15 tanks of oxygen.

INTERPRETATION OF DATA

The SDR, of course, is capable of a measurement of time only. The depth scale used is based on the velocity of 4,800 ft (800 fathoms) per sec, which is approximately the velocity of sound in water. In order to determine the true depth to a particular reflecting horizon, it is necessary to correct the depths shown by the SDR for the velocity of sound in the water and in the sedimentary column.

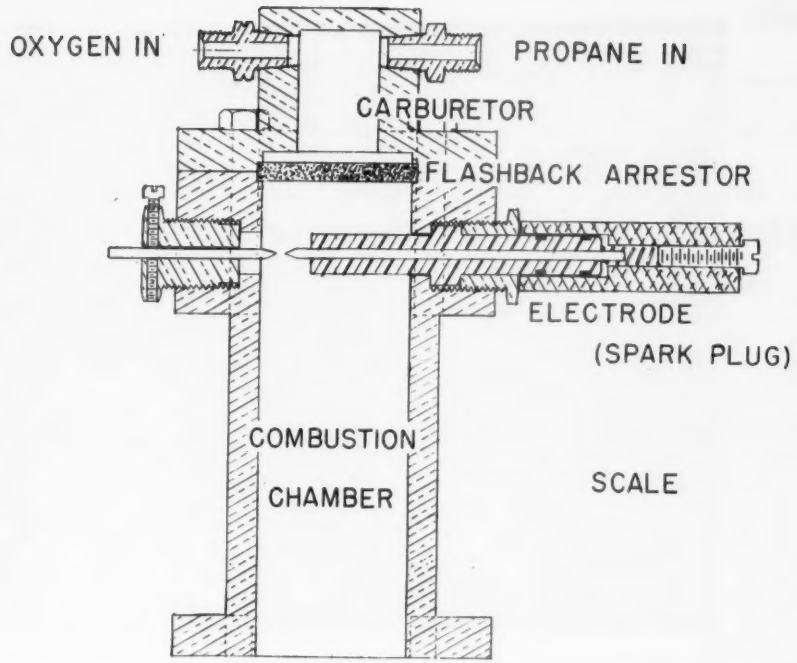

FIG. 5. The RASS combustion chamber. The propane and oxygen are introduced into the carburetor through separate vents. The gasses mix and pass downward where they are ignited by the spark plug. The flashback arrestor prevents continuous burning of the mixture in the carburetor. The resulting explosion exhausts through the bottom of the chamber directly into the water. The unit is contained in a small fish and towed two to five feet below the water surface.

The velocity of the sound in the water can be calculated from a knowledge of the temperature and salinity of the water through application of suitable formulae and tables. For many areas of the world, these values are already known, and it is necessary only to refer to them.

The velocity of sound in the sedimentary column is more complex, however, and one of a number of auxiliary measurements must be made. Of these, seismic refraction profiles, wide-angle reflection profiles, and test borings have been used successfully.

A number of strategically placed seismic refraction profiles, reversed to give true velocity, permit one to correct the depth of the various reflecting horizons as given by the SDR. In addition, they serve to influence one's confidence in the horizontal correlation of the various horizons.

Velocities can likewise be determined through the use of wide-angle reflection

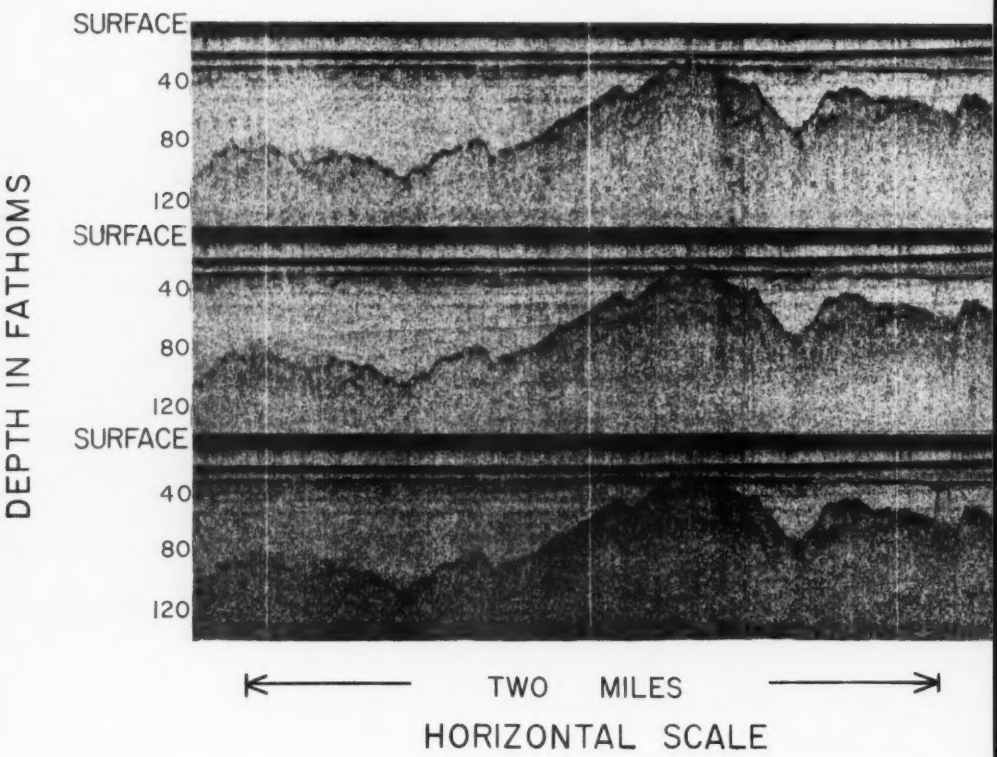

FIG. 6. A portion of a SDR record made in Long Island Sound using the Sparker at a repetition rate of three per second. The Time Variable Gain print amplifier was used to give a clear record of the shallow layers while using higher gain on the deeper bedrock. The repetition rate is varied by an auxiliary keying contact on the recorder.

profiles. In wide-angle reflection profiles the spread between the source and receiver is varied from zero to about four times the depth of the reflecting horizon. These profiles must be made in areas where the layering to be studied is horizontal and relatively free of relief. The SDR lends itself well to making wide-angle reflection profiles, since it is possible by the addition of a longer cable to achieve a varying physical separation between the receiving hydrophone and one of the sound sources. The hydrophone is permitted to drift from the ship, or in some cases it is carried out by a small boat and hauled in. By comparison with data from assumed velocity structures, it is possible to determine the structure in question (Officer, 1955).

Comparison with test borings that are available provide not only true depth

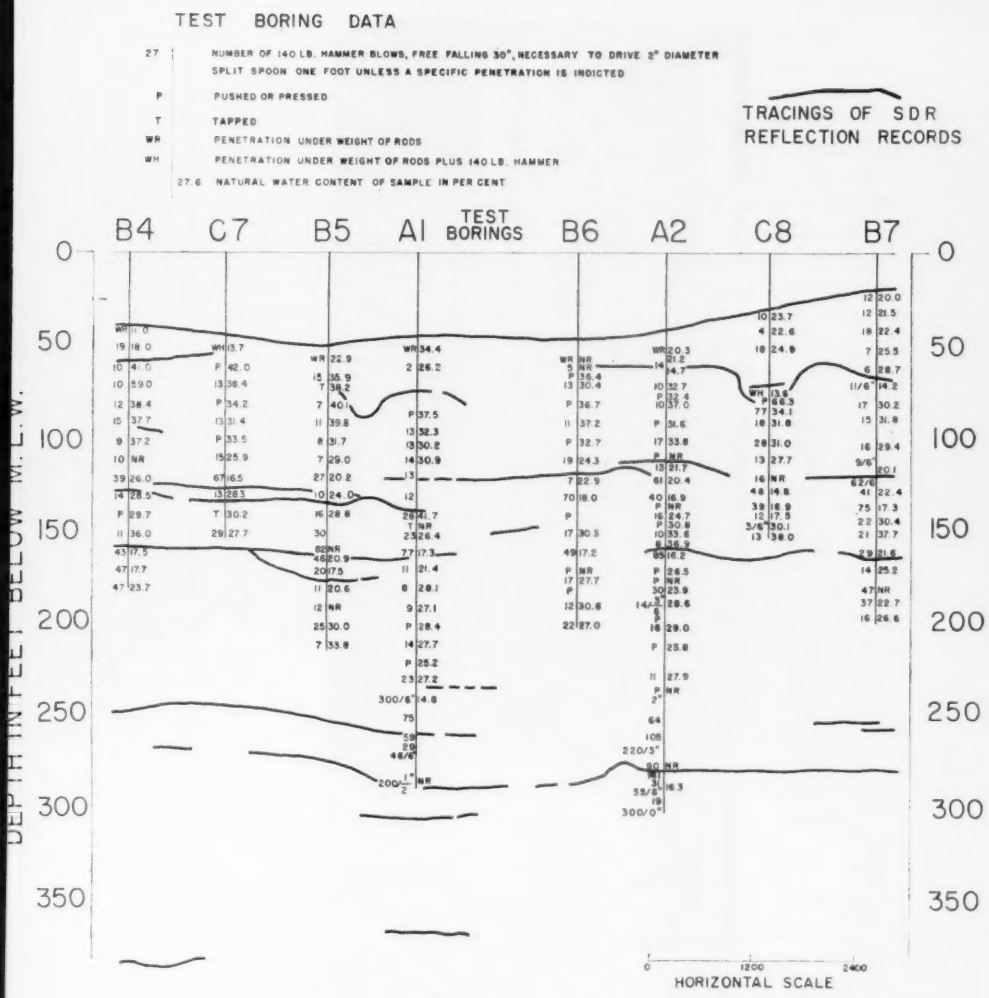

FIG. 7. Tracings of SDR (Sparker) reflections along with test boring data made in Chesapeake Bay for the Chesapeake Bay Highway Crossing. The sub-bottom reflections correlate well with two of the drilling parameters, either with the water content (porosity) of the sediment or with the resistance to mechanical penetration evidenced by the number of 140 pound hammer blows, free falling 30 inches, required to drive a two-inch diameter split spoon one foot.

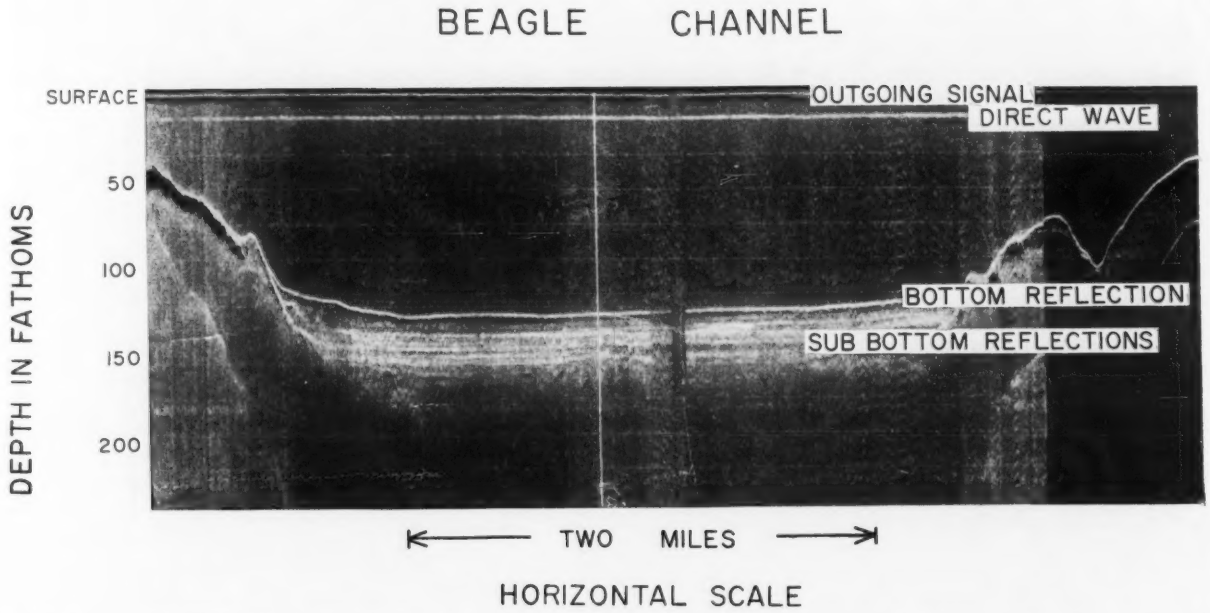

FIG. 8. A portion of a SDR (Sparker) record made in the Beagle Channel (Cape Horn). Visible are at least five sub-bottom horizons presumed to be the result of the Pleistocene history of the area.

to a reflecting horizon but furnish, as well, positive identification of the horizons. It has been found that of the test-boring parameters available in the field, two furnish extremely dependable correlation. These are the porosity (water content) of the sediments and the resistance to mechanical penetration as evidenced by the number of blows required to drive a standard split spoon core sampler. In Figure 7 a series of test borings are shown along with the SDR reflection tracings. These data were collected for the proposed Chesapeake Bay Highway Crossing[1] (1958). It will be noticed in all cases that an SDR reflection horizon correlates with a change in one or the other of the two parameters mentioned. In this particular case the accuracy of depth determinations of both SDR reflections and test boring data is plus or minus 5 ft.

In conjunction with sediment coring and drilling operations, the SDR provides a valuable guide to the selection of sampling sites. An excellent example of this is shown in Figure 8, made in the Beagle Channel (Cape Horn). At least five reflection horizons are visible. It is presumed that each corresponds to a glacial period; hence, in this relatively short vertical section, the Pleistocene history of the area would be preserved.

SUMMARY AND CONCLUSIONS

The Sub-bottom Depth Recorder (SDR) has been developed to study sub-bottom structures in water covered areas. It offers a choice of two sound sources, one using an electrical spark discharge and one a combustible gas explosion. The recording circuit offers selection of passband and time-variable gain. These arrangements give a maximum of versatility to the equipment for use in different areas and sub-bottom conditions.

The SDR has application in the study of geologic structures per se—in the interpretation and correlation of coastal structures. In foundation studies the SDR provides not only a guide toward the placing of strategically located test borings, but it provides an excellent horizontal correlation between borings.

ACKNOWLEDGMENTS

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Dr. W. Maurice Ewing was the Project Director and the authors wish to express their thanks for his advice and assistance throughout the project. The authors wish to thank Dr. J. Brackett Hersey of the Woods Hole Oceanographic Institution for this advice on the construction of the Sparker and to Drs. Charles L. Drake, John E. Nafe, George H. Sutton, J. Lamar Worzel, and Jack E. Oliver

[1] Personal communication with Sverdrup and Parcel, Consulting Engineers, St. Louis 1, Missouri.

for their contributions throughout the project. Mr. Stephen V. Chelminski contributed to the design and construction of the RASS.

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GEOPHYSICS, VOL. XXIV, NO. 4 (OCTOBER, 1959), PP. 761–789, 19 FIGS.

AFMAG—AIRBORNE AND GROUND*

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ABSTRACT

The existence of natural magnetic fields in the audio and subaudio frequency range has been known for some time. The primary source of energy for these fields is usually considered to be distant and local thunderstorms. Because of this origin, the fields are quasi-random with both amplitudes and directions changing drastically over short periods of time. Hence, use of these fields in geophysical prospecting has been extremely limited.

A new development, AFMAG, however, essentially eliminates the time variance in recording these fields without any sacrifice of the intelligence of their space variance. Since the space variance can be correlated with geologic features, AFMAG provides a new method of exploration with particular application to prospecting for conductive mineral deposits.

Instrumentation of the AFMAG method currently is available for both ground and airborne operation; the tilt of the plane of polarization of the natural magnetic fields is recorded simultaneously at two frequencies. Examples drawn from airborne and ground surveys show that the method has a much greater depth of exploration than its conventional cousin, the induction electromagnetic method. Numerous other advantages, such as the possibility of choosing discrete operating frequencies over a broad band from 1 cps to 1,000 cps, are discussed. The chief disadvantage of the method lies in a sometimes restricted daily measuring period during which the fields are of an amplitude too low to permit measurement with current instrumentation; this is not a serious problem and is being minimized as the technology improves.

INTRODUCTION

Electromagnetic surveys, both airborne and ground, have in recent years become the primary field activity in exploration for massive sulphides in most of Canada. Numerous specific techniques have been applied and most of these with success. However, all such methods bear one common inherent limitation: Depth of exploration is not great. On the ground this depth of exploration varies from 100 to 500 ft depending upon the technique employed. In the air it varies from 75 to 200 ft below surface. This limitation is imposed by the finite separation necessary between a transmitting coil and a receiving coil in order that the measurement of coupling between the two be reliable. The larger the separation between the transmitter and the receiver, the greater is the inherent depth of exploration; but so also are the requirements on signal-to-noise ratio in the receiver and transmitted signal strength made greater. Practical considerations associated with signal-to-noise ratio and signal strength so limit the useful depth of exploration to the maximum figures noted above of about 500 ft for ground equipment and about 200 ft (subsurface) for airborne equipment. These depths of exploration are not adequate for general world-wide coverage.

However, as Slichter (1955) has demonstrated, one of the main factors giving rise to a limited signal-to-noise ratio (atmospheric noise) may be put to good use as a source of energy to replace the artificially transmitted energy employed in

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conventional electromagnetic systems and thereby circumvent the depth limitation.

This has been done with AFMAG (Patent Pending), a product of ten years of research by the author and his associates.

The major problem to be faced in employing this natural energy is that it is very rapidly time-dependent. Separating the time-variance from the space-variance of these fields is a relatively simple theoretical problem as will be discussed below. Practically, however, the problem has been a difficult one; the difficulties were compounded by a world-wide lack of basic knowledge of the characteristics of the natural fields.

It is the object of this paper firstly to augment and review the state of knowledge of the natural audio and subaudio frequency magnetic fields with particular reference to the utility of this knowledge in employing AFMAG surveys and secondly, to discuss examples of airborne and ground AFMAG surveys. Some of the advantages and limitations of the method are thus made apparent.

NATURE AND ORIGIN OF NATURAL MAGNETIC FIELDS IN THE AUDIO AND SUBAUDIO FREQUENCY RANGE

Mode of Origin and Propagation

The rate of publication of articles on atmospheric "noise" in the audio and subaudio frequency range has increased markedly in the last five years. Although the amount of such data is still limited, we can conclude from it that the following are the chief sources of audio frequency atmospheric noise:

(1) thunderstorms,
(2) direct audio frequency energy from the sun filtering through the ionosphere,
(3) the generation of audio frequency magnetic fields by interaction of the corpuscular radiation from the sun with the ionosphere in the presence of the earth's main magnetic field, i.e., the gyromagnetic effect (Aarons, 1956)
(4) the generation of audio frequency magnetic fields by interaction of meteorites and the ionosphere (gyromagnetic effect),
(5) man-made noise. This could include fields due to urban electrification gyromagnetic effect from ionized blasts such as nuclear explosions, je. aircraft "vapor trails," etc.

World-wide thunderstorms would appear to be by far the most dominant source of energy, but this is by no means an established fact. In any event, the energy, whatever its derivation, is propagated in a spherical wave guide bounded by the surface of the earth and the lower surface of the ionosphere. Attenuation of the wave is therefore determined by the height of the lower surface of the ionosphere and by the physical properties of the surface layers of the earth and ionosphere. Neither of these surface layers is homogeneous, and hence, propagation is irregular geometrically. Further, the electrical properties of the ionosphere and

the height of its lower surface are time variant. Therefore, the attenuation is time variant.

Thus, the writer believes (but has not fully proved) that selective attenuation of components is far more important than spatial origin in determining the direction of polarization of the natural fields at any point in space.

The word "polarization" here is meant to refer to a "mean polarization," since the fields at any point in space possess a quasi-random character. The vertical component of overlapping individual pulses, which constitute the mean field, is normally lacking because of attenuation. Some horizontal polarization is evident, but is much less definite than the vertical polarization. Polarization becomes much more pronounced near a highly conductive geologic entity and the vertical component can become appreciable. Since thunderstorm sources are irregularly distributed throughout the world, this degree of disorder is to be expected. Fortunately, some degree of order exists; the ratio of vertical to (mean) maximum horizontal components, at any point in space, remains sensibly constant with time except when thunderstorms exist overhead.

Diurnal, Short Period, and Intermediate Period Time Variations in Field Strengths

A typical 24-hour recording of the time variation of one component of the magnetic fields is shown in Figure 1. This recording was made with a narrow band-pass (500 ± 5 cps) tuned coil receiver oriented so as to detect the maximum horizontal component. Two features of this recording are worthy of note:

(1) A sinusoidal diurnal variation in amplitude exists.

(2) Irregular short period variations in amplitude are recorded and appear as sharp "spikes" throughout the recording.

It should be stressed that the detector employed was narrow band, and hence the recorded 500-cps envelope is smooth relative to the existing pulsations of the field. An indication of this relative smoothness is afforded by expanding the time base as in Figure 2.

The irregular short period variation is caused by the almost random occurrence and distribution of the sources, while the sinusoidal variation is caused by a regular time-variant attenuation associated with changes in the height and electrical characteristics of the lower surface of the ionosphere, as referred to earlier.

During the day, the lower ionospheric layer is the D-layer at a mean height of 60 km. This high-loss layer disappears at night and the more conductive E-layer at 90 km becomes the upper bounding surface of the earth-ionosphere wave guide. Hence, typically, field strengths are lower during local daylight hours than at night.[1]

[1] Although the D- and E-layers are the accepted lower bounding surfaces of the ionosphere by day and by night, respectively, they are usually established as such by radar reflections and not by audio frequency measuring techniques. For this reason they are not necessarily the bounding surfaces for audio frequency energy, although most audio frequency propagation can be explained on this basis.

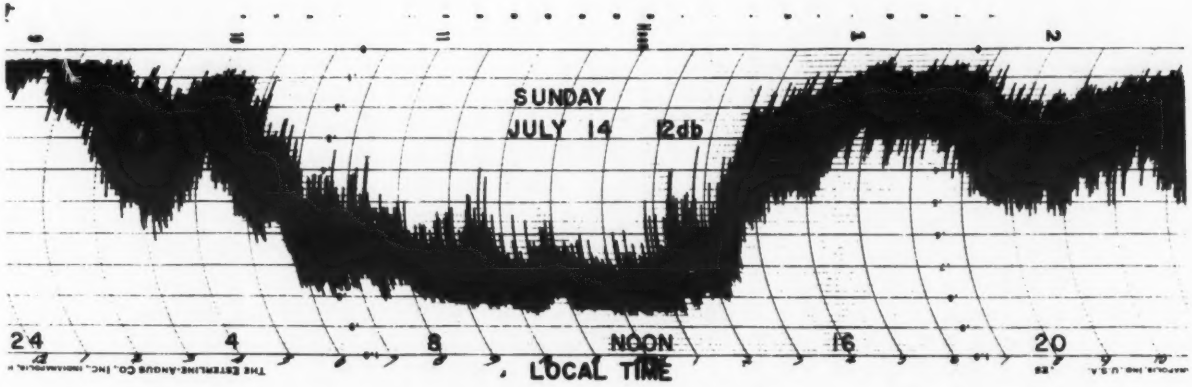


FIG. 1. Typical 24 hour recording of magnetic noise field. Location: Orangeville, Ontario. Date: July 14, 1957. Frequency: 500 CPS.

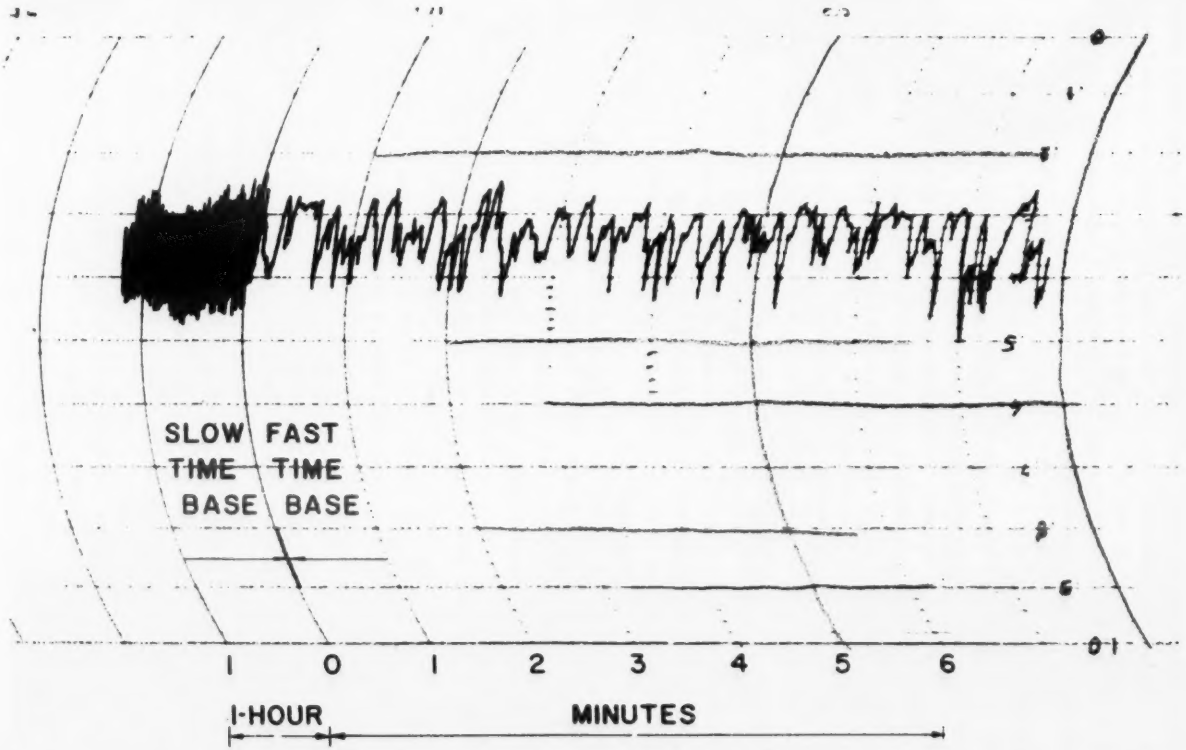


FIG. 2. Example of field strength variation, expanded time base. Location: Orangeville, Ontario. Date: September 23, 1958. Frequency: 500 CPS.

Superimposed on the short period and diurnal variations are irregular variations of intermediate periods. These may be caused by intermediate period time variance in the electrical properties of the ionosphere, in which case they may have the appearance of embayment "A" in Figure 3. Alternatively, they may be due to very local thunderstorms.

Local and Distant Sources

It is proposed that the total thunderstorm contribution to noise be considered as made up of local and distant parts.

The existence of these parts is clearly demonstrated by an analysis of Figure 4. The usual diurnal variation is present, but it is largely obscured by erratic and marked increases in intensity occurring between 9 A.M. and 12 noon for a station located at Lac La Ronge, Saskatchewan.

An illustration of the existence of distant sources is provided by recordings *A* and *B*, Figure 5. In this illustration, two stations over 2,000 miles apart detect almost identical patterns, although not necessarily identical amplitudes, for a period of several days. (Gain settings of the recorders at the two stations have not been cross-calibrated and, hence, a comparison of signal strengths is not available.) It is known that thunderstorms were not occurring near either site during the period of recordings. The two stations were Cross Lake, Ontario, and Tombstone, Arizona.

Although diurnal variation in field strength appears to be closely related to the development and dissipation of the D-layer of the ionosphere as the sun rises and sets, the correlation is not always obvious. For ideal correlation the daytime low in field intensity should be related to local time, and in many instances this holds true. For the recordings of Figure 5, an absolute time for the domain which includes the source of energy plus the two stations of observation needs to be considered. For example, events *A*, *B*, and *C* on the two recordings are separated by 2 hours and 25 minutes, 2 hours and 20 minutes, and 2 hours and 20 minutes, respectively. Since the two stations are situated 2 hours and 12 minutes apart geographically, the events *A*, *B*, and *C* occurred essentially simultaneously at the two localities. At this time of year (April), the nearest strong center of thunderstorm activity (World Meteorol. Organization, 1956) is probably in Central and South America (see Figure 6). Presumably the mean electrical characteristics and mean height of the ionosphere over a broad region spanning at least both North and South America must be considered. Note the disappearance of the regular diurnal pattern from 6 P.M., April 26, to 8 A.M., April 27 (times refer to the Tombstone record only, but the same phenomenon occurs on both recordings).

The "distant" sources are, in the literature, usually considered to be the three major world thunderstorm centers of Africa, South America, and the East Indies (see Figure 7). To provide a qualitative measure of the effect of the distance of one of these sources on the strength of the field at any point, the author made

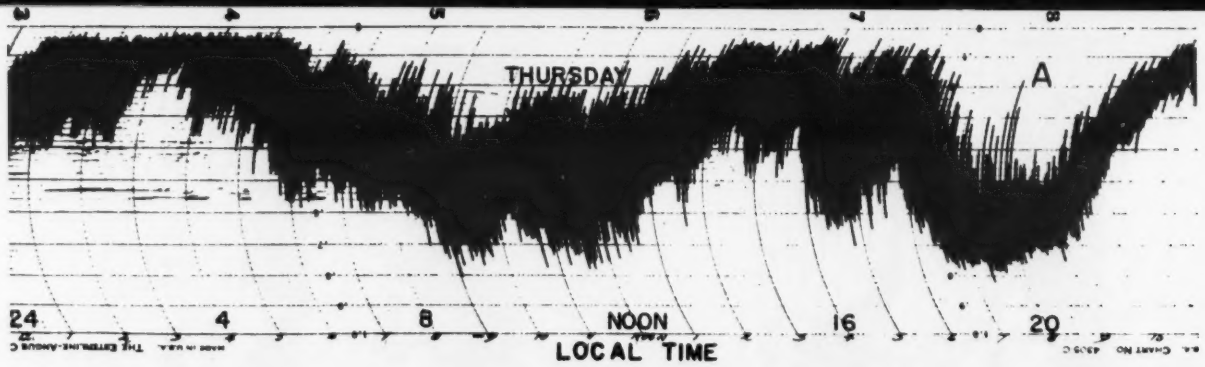


FIG. 3. Illustration of variation of magnetic noise field strength attributed to local variation in electrical properties of ionosphere. Location: Orangeville, Ontario. Date July 11, 1957. Frequency: 500 CPS.

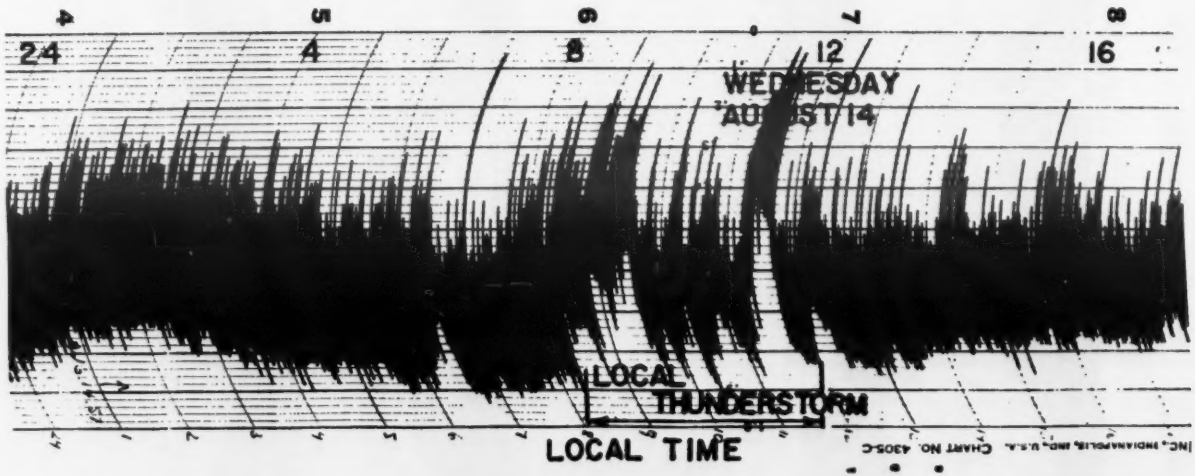


FIG. 4. Illustration of local thunderstorm contribution superimposed on distant thunderstorm contribution. Location: Lac La Ronge, Saskatchewan. Date: August 14, 1957. Frequency: 150 CPS.

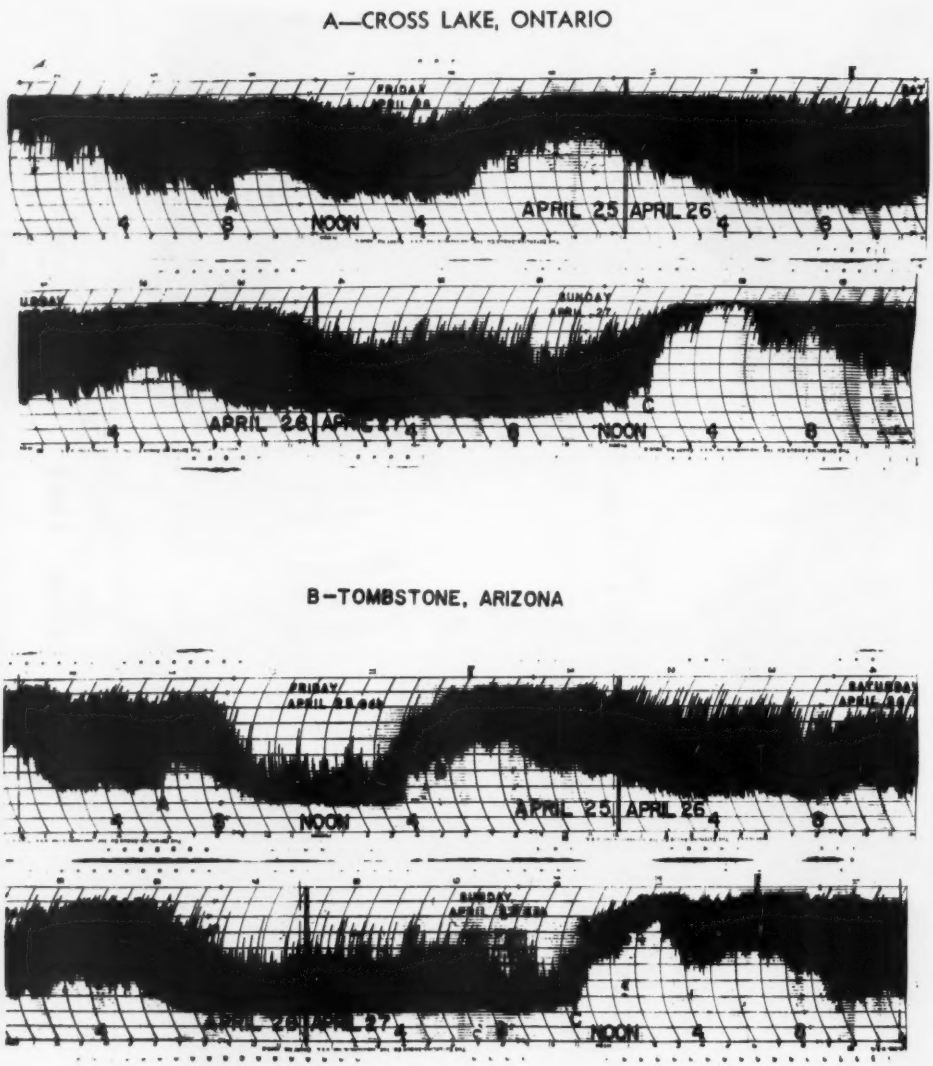


FIG. 5. Correlation of magnetic noise field strength between stations at Cross Lake, Ontario and Tombstone, Arizona for period of three days.

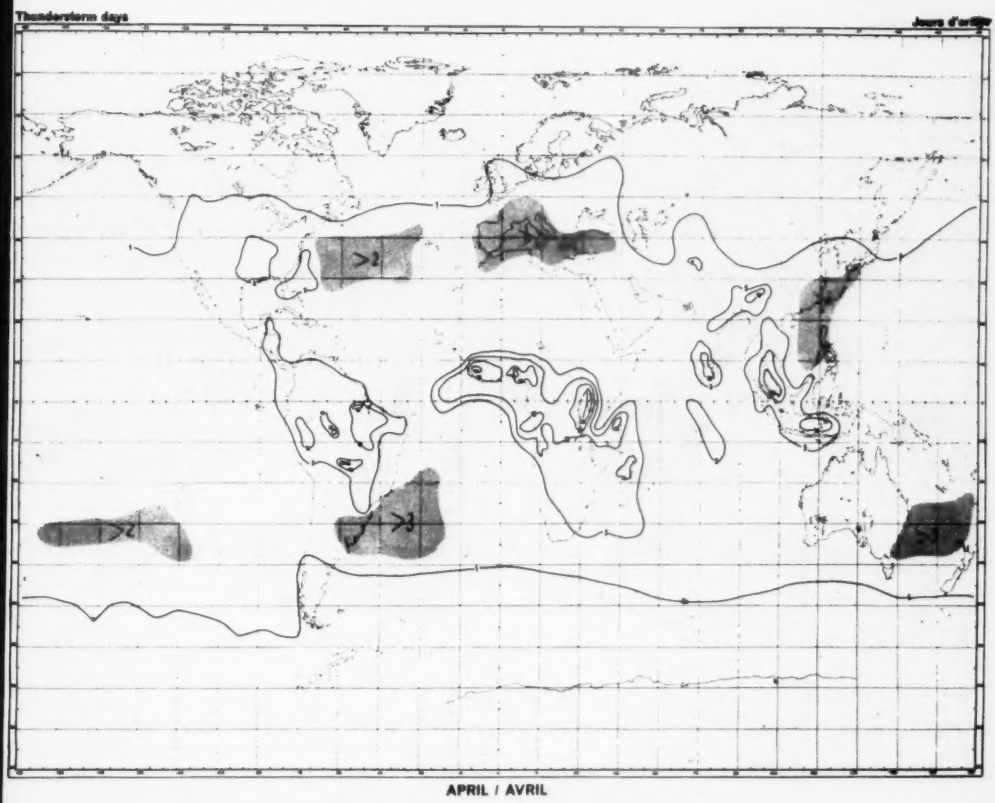


FIG. 6. World wide distribution of average number of thunderstorm days for month of April. (After World Met. Org.) Contour values 1, 5, 10, 15, 20.

measurements near Kitwe in Northern Rhodesia during the months of July, August, September, and October of 1957. July in Northern Rhodesia is a mid-winter month and seldom contains any thunderstorm activity (see Figure 8). At this time of year the center of the African thunderstorm activity is farther north. As October arrives, the thunderstorms in Northern Rhodesia become frequent and occur mostly about 4 P.M., local time. Violent bursts of lightning and thunder, accompanied by torrential rain, occur overhead most afternoons in the latter part of October (see Figure 9). Thus from July to October the thunderstorm energy center has moved south by perhaps 500 to 1,000 miles. A marked increase in audio frequency magnetic "noise" should, then, accompany this phenomenon. Such an increase may be observed by comparing the mean diurnal

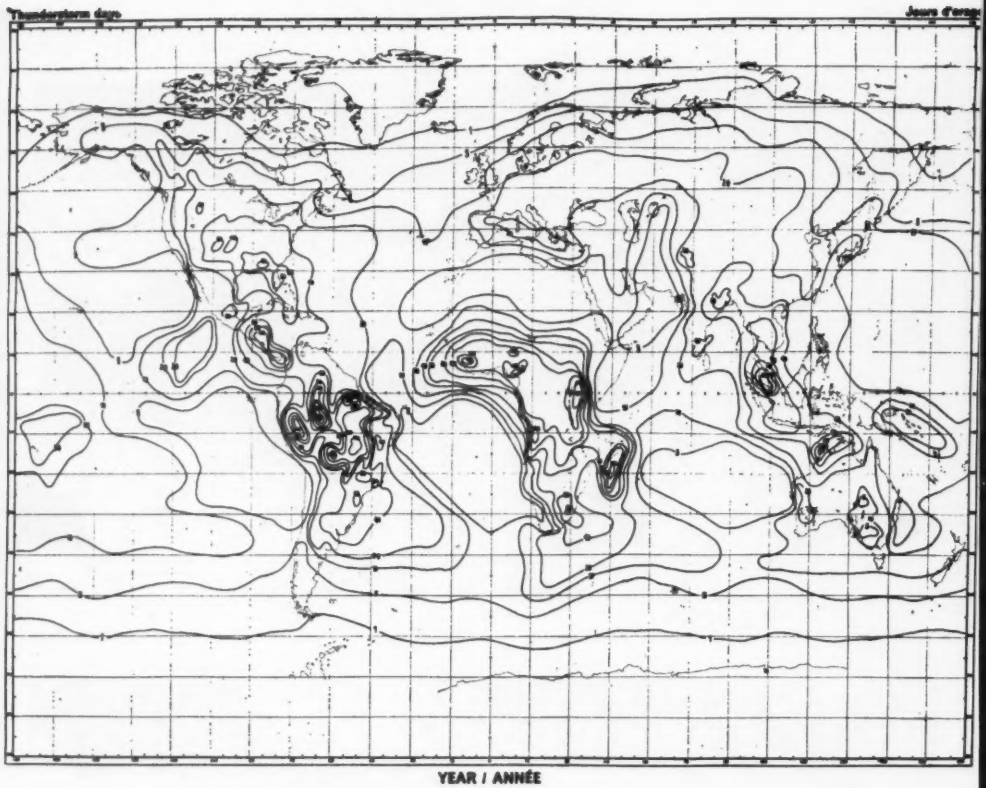


FIG. 7. World wide distribution of average number of thunderstorm days per year. (After World Met. Org.) Contour values 1, 5, 10, 20, 40, 60, 80, 100, 120, 140, 160, 200.

variations of magnetic noise at 175 cps for the months of July and October (see Figure 10). Note that, although there is a general increase in level throughout the day from July to October, the maximum increase occurs about 4 P.M., the time of the daily peak in thunderstorms. This feature is emphasized by plotting the difference of curves for July and October of Figure 10 as has been done in Figure 11. Obviously, the proximity of the 4 o'clock sources during October has led to a greatly enhanced "noise" level.

Secular Variations in Field Strength

Figures 1, 3, and 4 illustrate diurnal, intermediate period, and short period variations. By study of numerous graphs of this type, it is possible to establish that a secular variation in signal strength exists at any point in space. Perhaps

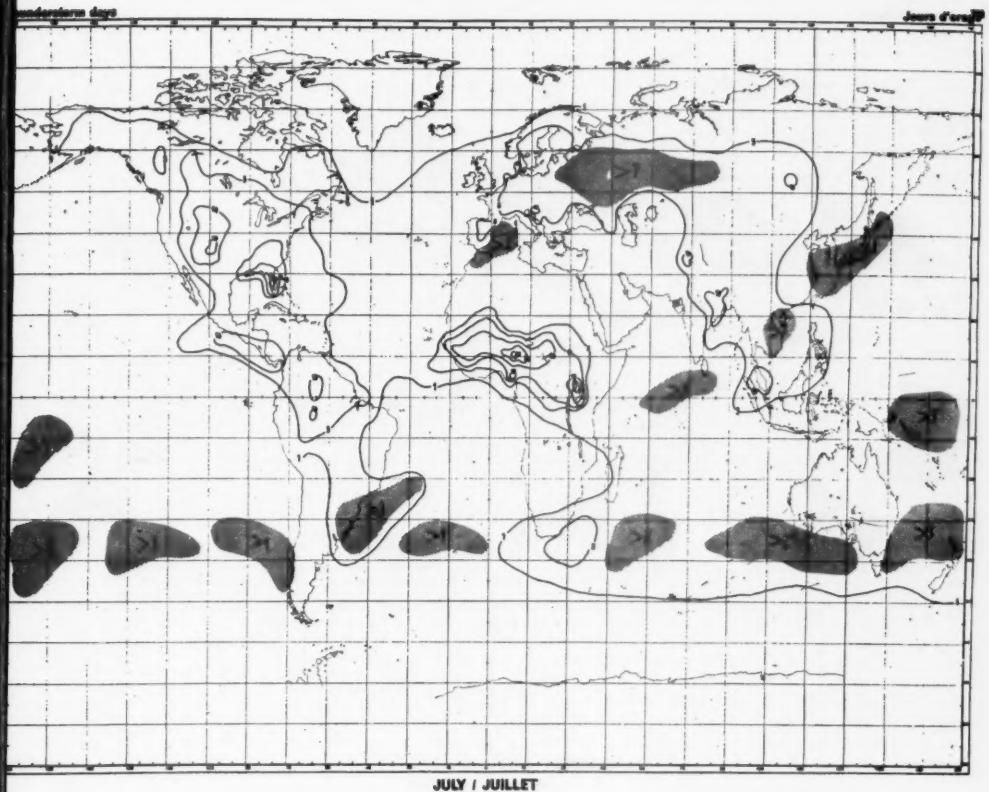


FIG. 8. World wide distribution of average number of thunderstorm days for month of July. (After World Met. Org.) Contour values 1, 5, 10, 15, 20.

the clearest illustration of the existence of secular variation is obtained by plotting the monthly mean field strength for any hour of the day. Such has been done for a station at Orangeville, Ontario, for the period February, 1957, to February, 1958, inclusive. The midnight and midday graphs of Figure 12 bear a marked resemblance to each other and portray a mean field strength during July, 1957, which is 20 db above the mean field strength for February, 1957, for the particular hours considered. The same general relationship holds true for all other hours of the day. Recordings have not been taken over a sufficiently long period to permit comment on the observed level increase from February, 1957, to February, 1958.

Source Spectrum and Frequency Selective Attenuation

One other facet of the origin and propagation of the "noise" fields is important to the application of AFMAG: frequency selective attenuation with

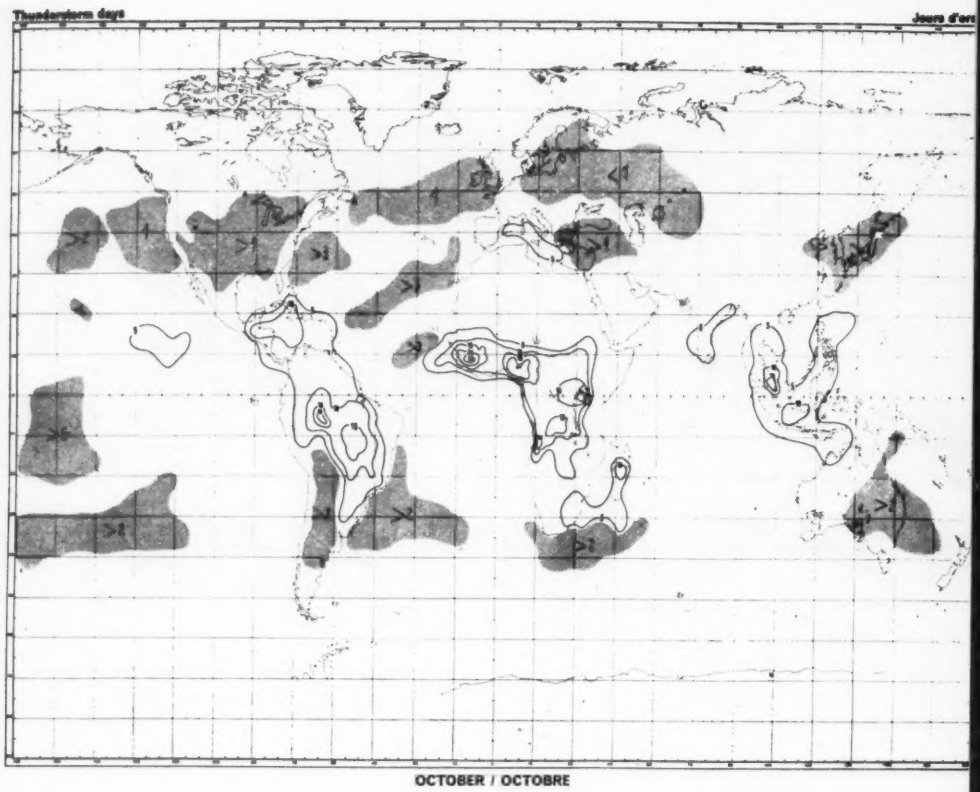


FIG. 9. World wide distribution of average number of thunderstorm days for month of October. (After World Met. Org.) Contour values 5, 10, 15, 20, 25.

distance, and frequency distribution of magnetic noise from a lightning discharge. Holzer, Deal, and Ruttenberg (1957) have studied attenuation in the range 45 cps to 6,000 cps and produced the data of Figure 13. Howe and Wait (1957) and Wait (1956) have developed a mathematical model of the earth-ionosphere wave guide which provides confirmation of these data. Watt and Maxwell (1957) plus Chapman and Macario (1956) have obtained experimental evidence which clearly illustrates the effects of both source spectrum and frequency-selective attenuation on the amplitude-frequency plot of atmospheric noise at any point in space (see Figure 14, after Chapman and Macario).

From Figures 13 and 14 we may conclude that if signal strength is a critical factor, then AFMAG should employ frequencies near the peak of the amplitude-

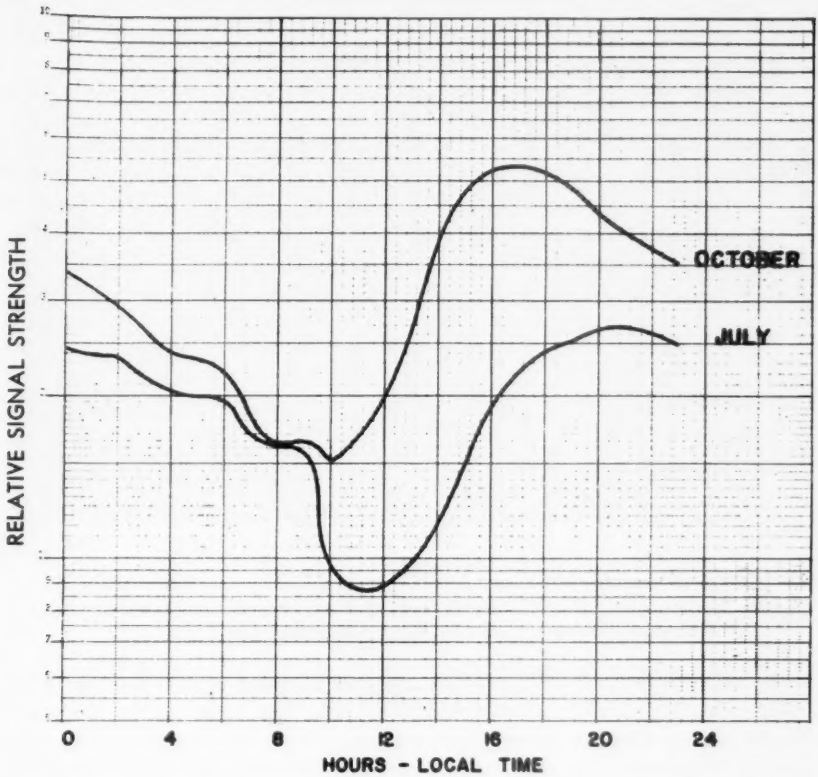


FIG. 10. Diurnal variation of natural magnetic noise obtained with coils tuned to 175 CPS. Kitwe, Northern Rhodesia—1957.

frequency plot. Little data are available from 45 cps down to 1 cps, but what is available suggests a decrease in signal strength with decrease in frequency in this region. Hence, a range of frequencies of from, say, 10 cps to 500 cps is suggested for use in prospecting.

AFMAG DESIGN FACTORS

Minimizing the Effect of Time Variations

The first and foremost problem to be faced in attempting to utilize the natural magnetic "noise" fields is effective elimination of short period time variations from the quantity measured. The short-period time variations in amplitude frequently produce 40-db changes in recorded signal level, whereas a sizeable ore

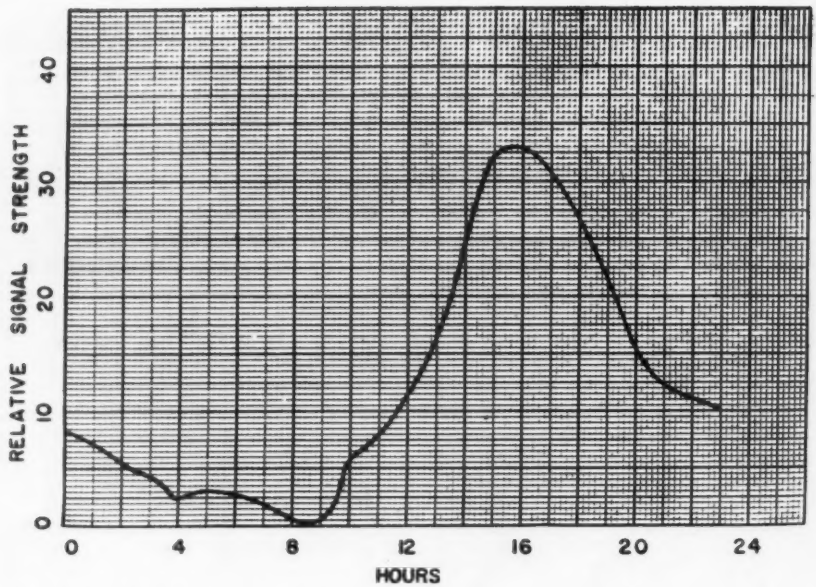


FIG. 11. Local thunderstorm contribution to diurnal variation of natural magnetic noise obtained with coils tuned to 175 CPS. Kitwe, Northern Rhodesia—1957.

body may produce no more than 6-db change in recorded level. It thus becomes imperative to introduce a comparator measuring technique wherein the time variations affect two detectors identically, yet space variations affect them differently. Cagniard (1953) accomplished this in the magneto-telluric method by "comparing the horizontal components of the magnetic and electric fields associated with the flow of telluric currents." It is accomplished in AFMAG by the simple expedient of measuring the tilt of the plane of polarization of the natural alternating magnetic fields (this is achieved by measuring the ratio of two components of the magnetic field).[2]

In the airborne version of AFMAG, the orientation of coils is that shown in Figure 15, and hence the components detected are those at 45° to the horizontal

[2] Cagniard's concept is that telluric currents are the primary source of energy, whereas the writer employs the concept of alternating magnetic fields caused by atmospheric electrical discharges as the primary source of energy. Under the latter concept, the existence of telluric currents is only a necessary phenomenon in the anomalous state and not in the normal state. This difference of concept is of considerable significance in the application and interpretation of AFMAG and magneto-telluric surveys, since Cagniard presupposes a horizontally uniform current sheet, whereas anomalies sought by AFMAG are those associated with deviations from a uniform or zero current sheet. Cagniard intended his method for use in uniform horizontally stratified sedimentary basins, whereas AFMAG is intended to locate variations from such horizontal uniformity.

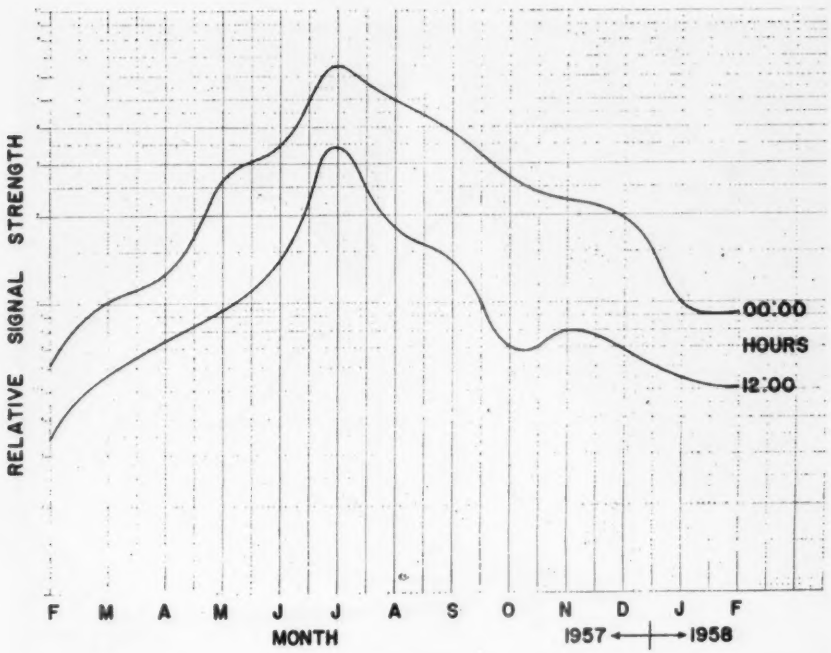
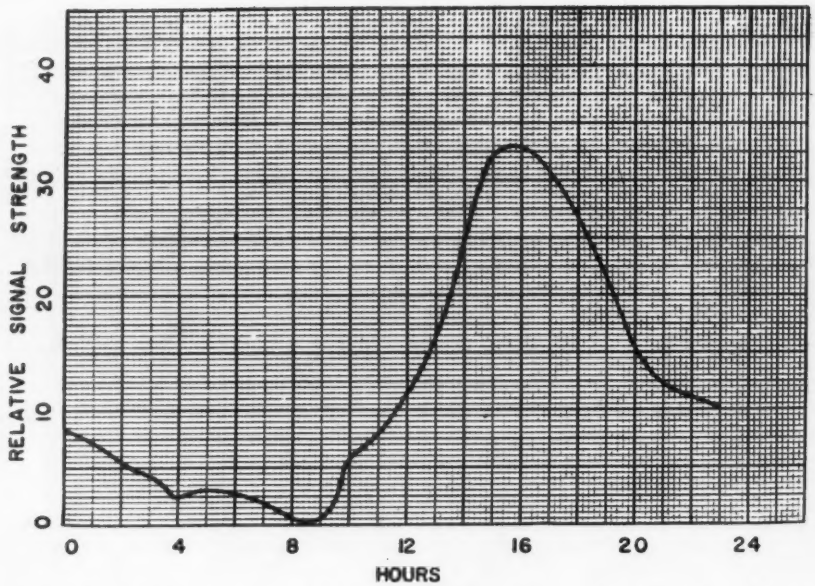


FIG. 12. Secular variation of natural magnetic noise obtained with coils tuned to 500 CPS. Orangeville, 1957–1958.

in the direction of flight. The manner in which these components are compared electronically is such that the deflection of a pen on a chart recorder is approximately proportional to α, the tilt of the plane of polarization. Since short-period time variations of signal strength affect both coil systems simultaneously, and to the first order by the same amount, the output of the comparator of Figure 15 approaches zero for such changes in amplitude of the natural fields. Time variations of amplitude are thereby eliminated to a first order from the quantity recorded.

On the other hand, should the direction of polarization in the vertical plane through the two coils vary with time, then these variations would be recorded. Fortunately, for all but very local noise sources, these polarization variations are of the second order and are of a shorter period than true anomalies; they may be largely eliminated by electronic smoothing. Nevertheless, they may preclude use of airborne AFMAG occasionally.

Also, of course, because it is impractical to construct two truly identical electronic systems, very large changes in signal strength are sometimes recorded despite the employment of the comparator system. Again, such changes are almost



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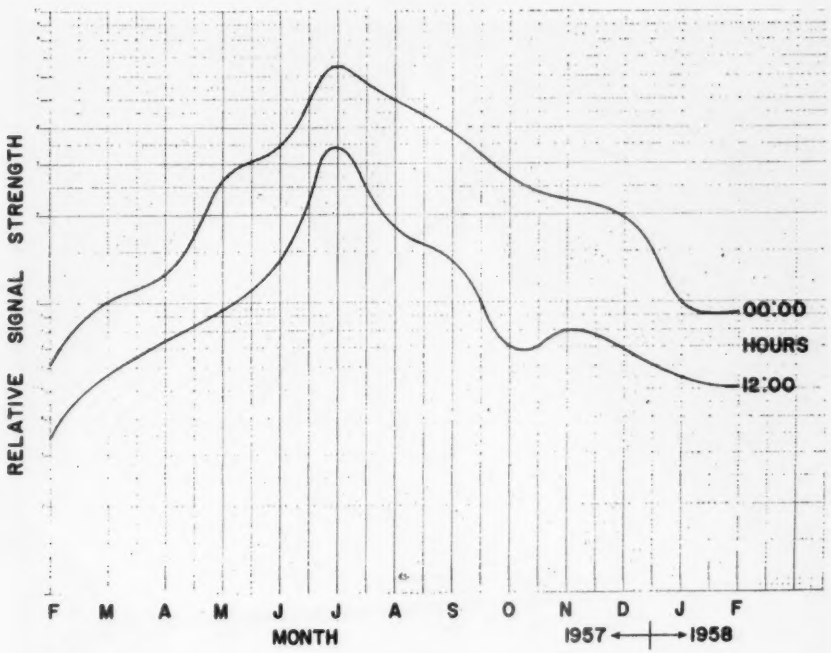

FIG. 12. Secular variation of natural magnetic noise obtained with coils tuned to 500 CPS. Orangeville, 1957–1958.

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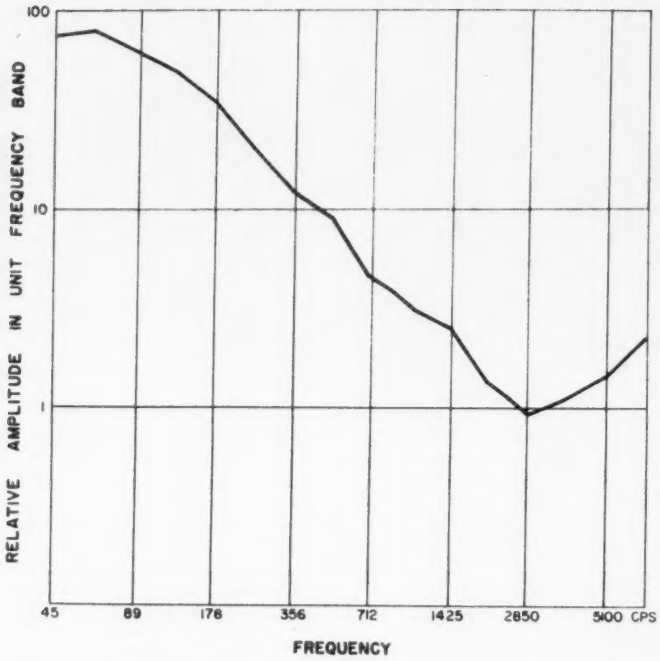

FIG. 13. Amplitude-Frequency plot of natural audio frequency magnetic noise. (After Holzer, Deal and Ruttenberg.)

always associated with a high proportion of local noise relative to distant noise and can be reduced by electronic smoothing.

Securing Adequate Signal-to-Noise Ratio

Up to this point in our discussion we have used the word "noise" to apply to natural alternating magnetic fields or "atmospheric noise." Conventionally the term "noise" also includes the following:

(1) thermal agitation noise in the detecting coils,
(2) thermal agitation noise in the input circuit of the first amplifier,
(3) tube noise in the first amplifier,
(4) noise mechanically induced in the detecting coils (this may include magnetostrictive effects; vibrations of the coils and/or nearby ferrous objects in the earth's main magnetic field, plus changes in the effective area of the coils),
(5) aircraft noise (this may include the electromagnetic field of the ignition system plus the movement of the aircraft, as a metallic "anomaly," relative to the detecting coils),

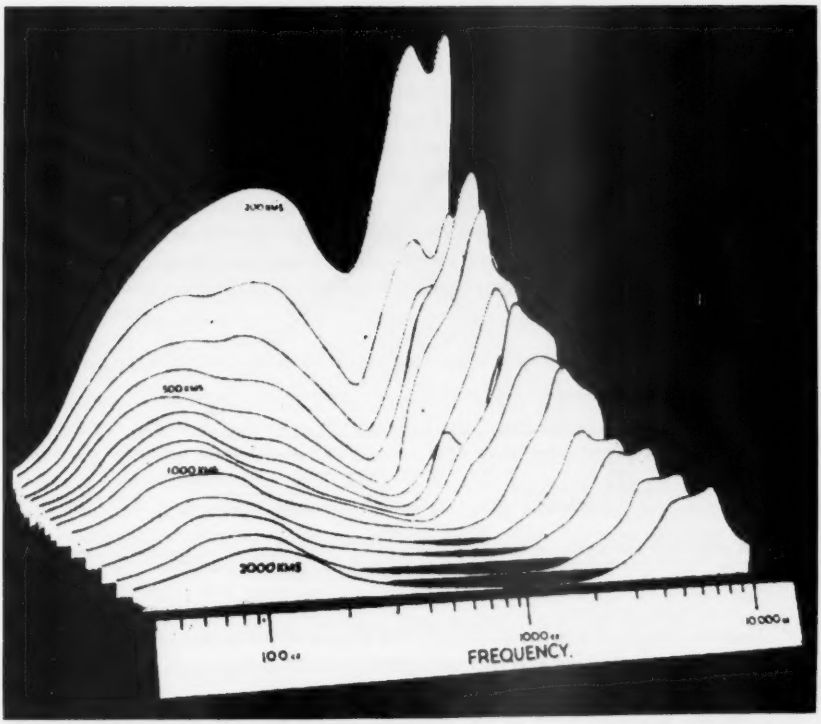

FIG. 14. Model showing source spectrum and attenuation of field of average daytime lightning stroke. (After Chapman and Macario.)

(6) geologic noise.

For the purposes of this discussion "atmospheric noise" is considered as the signal and the remaining six items as true noise.

Geologic noise is the background of minor anomalies of no significance upon which the significant anomalies are superimposed. This is an inherent limitation in any geophysical system and is usually removed by some form of human smoothing. In airborne AFMAG a minor amount of geologic noise normally is removed by electronic smoothing, but this is adjustable.

Aircraft noise is minimized by placing the detecting coils in a "bird" trailed some 200 to 500 ft beneath and behind the aircraft. Ignition noise is also suppressed by standard methods as far as possible.

Mechanically induced noise is minimized by:

(1) ensuring that mechanical resonances lie well beyond the bandwidth of frequencies admitted by the high Q detecting circuits,

(2) appropriate design of coils to ensure rigidity and no significant magnetostriction (if iron cores are employed).

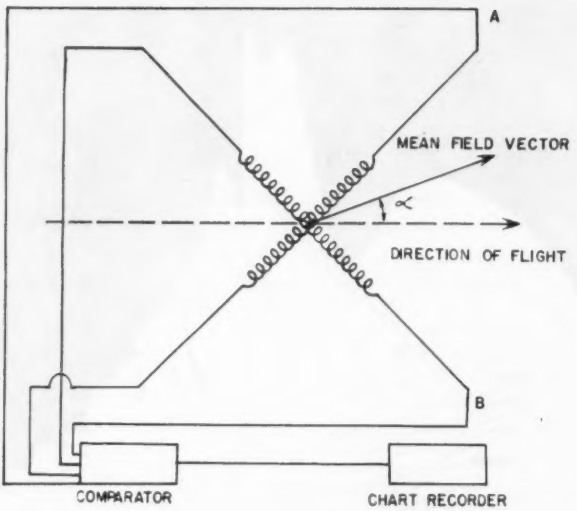

FIG. 15. Simplified representation of measurement of tilt (α) of plane of polarization in direction of flight by airborne AFMAG system.

Correct design of the input circuit and choice of tubes can ensure that tube noise in the first amplifier and thermal agitation noise in the input circuit are both small relative to thermal agitation noise in the coils.

Thermal agitation noise in the detecting coils is then left as the fundamental limitation on a high signal-to-noise ratio. An extremely high ratio of pickup factor (turns-area-frequency product) to resistance of an individual coil can eliminate this factor entirely, but only at the expense of an impractical weight of wire in the coil [see Slichter (1955)]. Thus coil thermal agitation noise theoretically remains as the basic limitation of the detecting system. When the atmospheric noise drops to a level which is of the order of only 6 db above the coil thermal agitation noise, then measurements of atmospheric noise are precluded. This does occur for both airborne and ground AFMAG as the atmospheric noise reaches its lows in secular and some diurnal variations. However, with airborne AFMAG, the vibration of the detecting coils in the very strong earth's main magnetic field frequently, if not usually, produces noise which is somewhat above the level of the thermal agitation noise of the detecting coils. Hence, in practice this factor usually dictates the times at which the airborne system becomes inoperative. This is understandable when one considers that the earth's main field is, say, $6\times10^{4}\gamma$ whereas the thermal agitation noise is at a level which would permit detection of a field of less than $10^{-5}\gamma$. Mechanical and electrical discrimination cannot always be adequate to work against a factor of nearly 10^{10}. Of course, the more turbulent the air, the greater and more rapid is the angular rota-

tion of the detecting coils in the earth's main magnetic field and consequently the greater is this particular noise contribution.

Secular variations in field strength limit the annual period of applicability of the method. Up until the last six months, the use of ground AFMAG has been limited to the period April 1 to November 1, and airborne AFMAG from about May 1 to October 1 in Northern Canada. Recent equipment improvements suggest that use of ground AFMAG may be extended appreciably beyond these limits. Naturally, in regions closer to year-round thunderstorm sources, AFMAG conceivably could be employed without interruption. Experience with early model AFMAG units in Northern Rhodesia suggested that even under local midwinter field conditions, six hours of daylight operation were to be expected on the average.

Dynamic Range Requirements on Amplifiers and Detectors

The field intensities at any point in space can vary by several tens of times over periods of a fraction of a second. Narrow band pass circuits reduce these extreme variations considerably (Fulton, 1957), but even so, the dynamic range of voltage from the pickup coils places strenuous requirements on linearity of amplifiers and detectors. This is particularly true in a comparator system where any non-linearity existing must be identical in the two channels in order not to result in poor cancellation. Various electronic dodges may be introduced to overcome this difficulty but each leads to additional complexity and/or difficulties. Thus dynamic range of signal strength can, on rare occasions, lead to difficulty of measurement.

In this regard, distant sources would appear to produce fields of lesser dynamic range than local sources. However, this point requires further study before any quantitative information can be offered. Quite possibly the more regular fields of distant sources are due to the greater number of initiating events. The time interval between individual pulses and the dynamic range of these pulses both require consideration in prospecting instrumentation. Obviously a long interval between pulses can lead to difficulties in measurement or to erroneous recordings since if the time interval were infinite, only the meaningless ratio of thermal agitation noises in the two detecting coils would be measured. This difficulty has been experienced at times of extremely low field strengths.

Choice of Frequencies for Prospecting

It may be said that the AFMAG method is similar to a conventional inductive electromagnetic method with the transmitter removed to infinity. This analogy provides a useful concept for interpretative procedures. Typically, inductive electromagnetic systems employ a frequency of 400–1,000 cps if of the single frequency type, and of 400–1,000 cps and 2,000–5,000 cps if of the dual frequency type. It is known from work in these frequency ranges that an increase in the transmitter-receiver spread is equivalent to an increase in the frequency when tracing long linear conductors. For instance, at a spread of 200 ft a poorly con-

ductive fault zone may not be detectable at 1,000 cps. On the other hand, increasing the spread to 600 ft or the frequency to, say, 2,000 cps may raise the response of the fault above the lower limit of detectability. Other similar examples might be cited. Hence to provide the same range of responses, AFMAG should operate, because of its effective infinite spread, with somewhat lower frequencies. On the other hand, the frequencies should not be lowered too far or significant anomalies will begin to drop out. Hence nominal operating frequencies of 500 cps and 150 cps have been chosen and are employed simultaneously in one instrument.

In order to minimize pickup of fields of power lines, the actual operating frequencies are adjusted to 150 cps and 510 cps to avoid harmonics of 60 cps power line fields and to 175 cps and 475 cps to avoid significant harmonics of 25 cps and 50 cps power line fields. Even so, AFMAG surveys may meet with some interference near power lines—and for that matter near some telegraph and telephone lines. Of course, in some instances, the artificial fields of power lines can be used to advantage to replace the natural fields. Conductivity analysis of buried conductors, normally provided by comparing the ratio of the 150 cps to the 510 cps responses, is more difficult to apply in these power line areas.

For some problems, use of still lower frequencies may be desirable. This seems to be feasible, at least down to 10 cps, as indicated earlier. Beyond that range possibly lies hope for application of AFMAG to deep petroleum exploration. Even with frequencies currently employed, exploration for saline domal structures at depths as great as 3,000 to 5,000 ft would appear to be practicable.

RESULTS OF FIELD SURVEYS

Ground Surveys

Numerous examples of ground surveys and field techniques were presented in an earlier paper by the author and his associates (Ward et al 1958). The reader is referred to these results which demonstrate fairly well the advantages and limitations of ground AFMAG surveys. Hence only one illustration is presented herein of results obtained with ground equipment; Figure 16 contains dual frequency AFMAG dip angle profiles obtained over a tabular pyrite-pyrrhotite sulphide body. Standard interpretative procedures used on data from vertical coil electromagnetic surveys may be applied (with some modifications) to data from AFMAG surveys. Thus the following analysis is derived:

(a) The lateral positions of the conductor-axes are located readily from the tilt angle "crossovers" at the two frequencies. The shift between the two crossovers is indicative of inhomogeneity of the conductive body.

(b) Conductivity is estimated semi-quantitatively by recording the ratio of peak-to-peak tilt angle amplitudes at the two frequencies. For this example, the ratio is

$$\frac{7+35}{23+34} = 0.74.$$

(c) Depth to the top of the conductor can be estimated from the slope of the

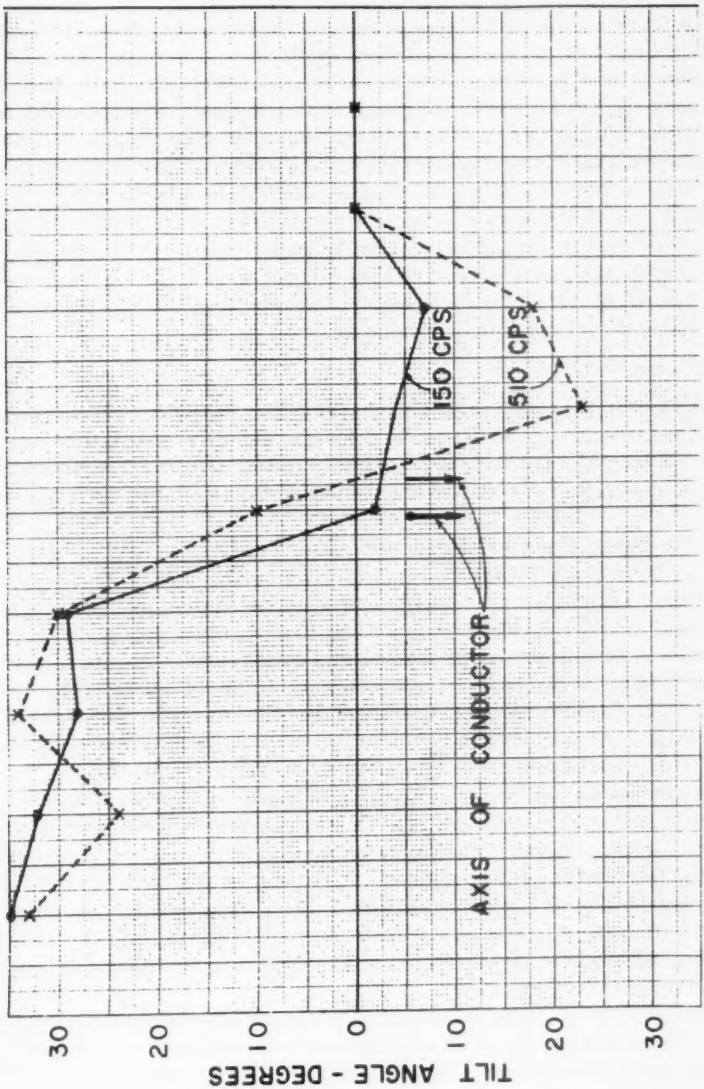

FIG. 16. Dual frequency AFMAG tilt angle profiles over sulphide zone.

"crossover." A depth perhaps as shallow as 25 ft is interpreted from Figure 16.

(d) Depth extent affects the slope of the profile beyond the peak and can be estimated provided the profile is of sufficient length.

(e) The effective dip of the conductive body at each frequency is determined by measuring the assymmetry of the profile at that frequency. An expression of this is, 7/30 at 150 cps, and, 23/34 at 510 cps, both indicating a dip to the east. Comparison with scale model experiments leads to a quantitative interpretation of these latter figures. Usually a gross inhomogeneity of the sulphide body would lead to such a marked difference in dips interpreted from the two profiles. In this example, however, the effect of an adjacent conductor near 4+OOE probably is also affecting the two profiles to a different degree and hence rendering the normal analysis invalid. However, the example is included because it is a good one for demonstrating the principles of interpretation.

Airborne Surveys

As discussed in the earlier paper (Ward et al 1958), the technique of measurement on the ground is first to determine the mean azimuth of polarization, then to determine the tilt of the plane of polarization in that azimuth. This procedure is repeated at discrete intervals and the tilt angle readings plotted up in profile form.

Airborne operation requires modification of this procedure. Rather than determine, by horizontal polarization measurement the azimuth in which tilt angle readings are to be recorded, the tilt angles are measured in the direction of flight.

The flight direction is chosen perpendicular to strike of regional geologic features, which in turn tend to align the noise fields perpendicular to themselves. Thus the measurements are, on the average, made in the azimuth of mean polarization. It should be borne in mind here that the horizontal polarization is not a definite direction for all noise pulses, but is a mean direction for them. Hence the compromise adopted for the airborne system is a reasonable one.

The tilt of polarization, which is clearly defined and is zero in the normal state, is recorded continuously on a paper tape. In fact, two such recordings are made, one for each of the two operating frequencies. In addition, the signal strength at each of the two frequencies is monitored continuously so that gain settings can be made appropriate to the noise field levels. These signal strength recordings also afford the interpreter the opportunity to study abnormal behavior of the noise fields and so assess the importance of such field characteristics as dynamic range and interval between pulses.

Centering of the tilt angle recordings on the paper tapes is made arbitrarily at the start of each flight line in an area assumed to present only zero tilt angles. Obviously some centering or zero error can arise by this procedure, but since only changes in the tilt angles are indicative of buried conductors, the absolute level is relatively unimportant. In any event the absolute level can often be determined by inspection of the paper tapes. In addition the centering control is calibrated in terms of equivalent change in tilt angles.

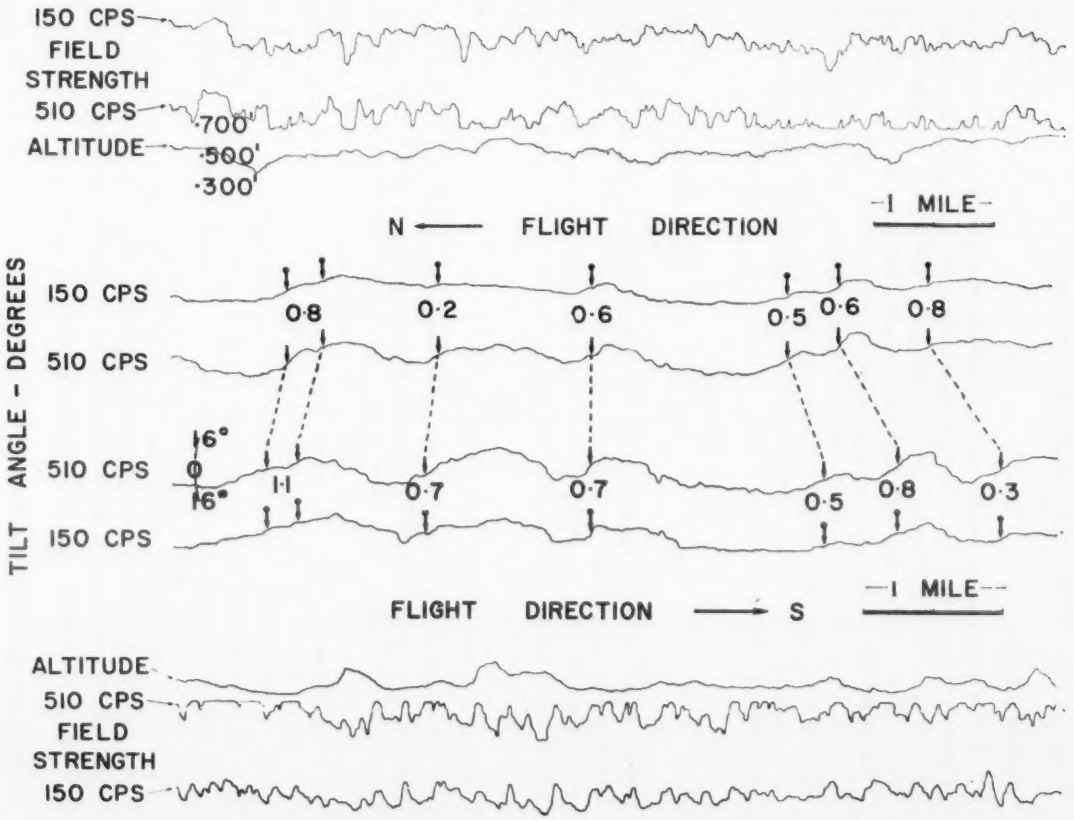

FIG. 17. Typical adjacent airborne AFMAG recordings.

Mean terrain clearance, as measured by a radio altimeter is continuously recorded. The customary positioning by strip film is employed.

Typical Recording

Two adjacent paper tape recordings from an airborne survey are shown in Figure 17, where some of the items discussed above are indicated. The locations of conductive bodies are determined by noting the mid-point of an inflection in the tilt angle profile as has been done on the tapes. Only an inflection from negative on the left to positive on the right is significant according to the convention adopted for recording the tilt of the plane of polarization (opposite convention normally adopted for ground data). Semi-quantitative estimates of conductivity are again provided by measuring the ratio of peak-to-peak amplitudes of the anomalies at the two frequencies, i.e.,

$$\frac{150 \text{ cps}}{510 \text{ cps}} .$$

These values will range from 0 to 1, as the conductivity increases from very poor to excellent. Such values are noted on the paper tapes. Depth and depth extent estimates are made according to the criteria discussed for the ground survey data. Dip estimates could be made but are seldom necessary in interpretation of these airborne profiles.

Decrease of Anomaly with Aircraft Height

To determine the decrease of response of a long linear conductor with altitude, the test depicted by Figure 18 was made. It is interesting to note that the anomaly is detectable at aircraft altitudes as great as 3,000 ft (bird height approximately 250 feet less in all cases). The amplitude fall-off law is of the order of the inverse first power of altitude as predicted by theory. For conductors approaching a more spherical shape the fall-off should be governed by an inverse cube law and hence a conductive ore lens of the order of one-quarter mile in maximum dimension would cease to give a recognizable anomaly signal at altitudes of the order of 1,000 ft or greater. This would appear to be borne out by experimental evidence over the Mattagami orebody in Northern Quebec.

In contrast, airborne electromagnetic surveys seldom record a response when the aircraft is at an altitude in excess of 750 ft. Thus, as much as another order of magnitude in depth of exploration for massive sulphide bodies is available with AFMAG compared to conventional electromagnetic surveys.

Comparison of Airborne AFMAG and EM Data

A comparison of airborne AFMAG and airborne electromagnetic anomalies over the Whistle Mine, near Sudbury, Ontario, is provided in Figure 19. Note that the influence of the ore zone is measured at a much greater lateral distance

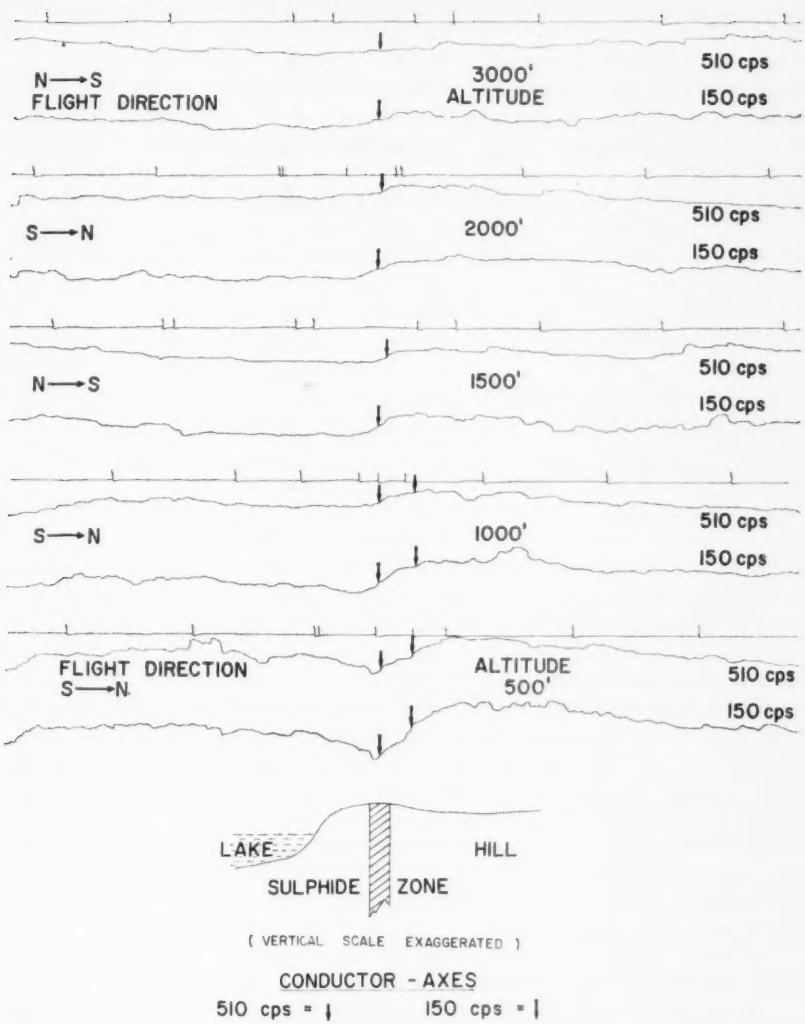

FIG. 18. Variation of anomaly with aircraft altitude over long linear conductive body.

from it with AFMAG than with a conventional airborne electromagnetic system. Thus, greater lateral range is indicated; this leads to a greater probability of detection of such orebodies. Note also the greater percentage of total field that the anomaly is with AFMAG as opposed to EM.

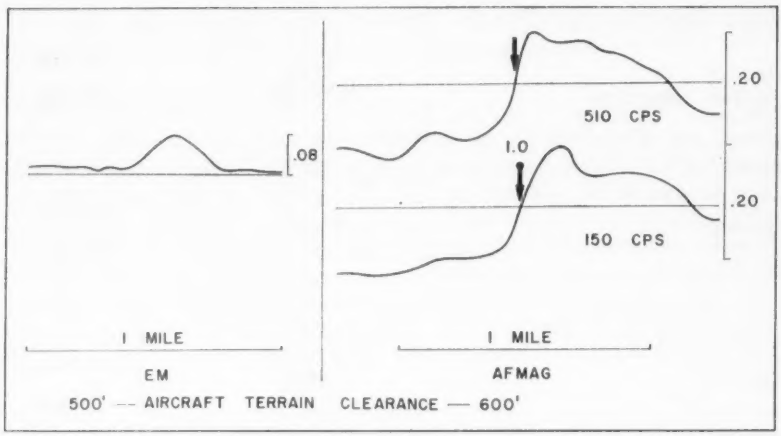

FIG. 19. Comparison of airborne EM* and airborne AFMAG responses over Whistle Mine, Sudbury District.

* After Slichter, 1955.

CONCLUSION

Although there is much to be learned concerning the basic theory, application, and interpretation of AFMAG, production airborne and ground surveys with the system over the past three years have demonstrated its utility as a means of locating and evaluating buried conductors.

On the basis of the evidence presented in Figure 18, it would appear practical to explore for mining targets in mountainous terrain where aircraft terrain clearances of necessity must be extremely variable and sometimes large. Similarly, depths of exploration in areas of deep oxidation or areas of deep valley fill are adequate to reach targets which up to now have been excluded from aerial electrical prospecting. It seems reasonable to speculate that such petroleum exploration targets as saline domal structures, in view of their large size, may be detectable at depths of the order of 3,000 to 5,000 ft. No experimental work has been performed in this respect as yet.

AFMAG may provide a greater probability of detection of certain ore zones when investigations are carried out on a standard grid pattern.

To achieve these major advantages requires, at present, a concession in the times of the year during which the method may be fruitfully employed. In particular, the winter months in temperate climates are not currently satisfactory operating times, unless observations are made at night. A few summer days or portions thereof similarly may be unsuitable for observations because of excessive reduction in the strengths of the natural fields. These problems are not of significant importance in tropical and sub-tropical areas where the system is likely to have its greatest application.

ACKNOWLEDGMENTS

The author wishes to make it clear that the development of airborne and ground AFMAG equipment is almost entirely the work of his former associates, Messrs. W. O. Cartier, H. A. Harvey, G. H. McLaughlin, and W. A. Robinson. To them he is indebted for the opportunity to be associated with such a development and for constant counsel.

American Metal Climax, Inc. financed a large portion of the research on this project. Thanks are due to the management of the Mining and Exploration Department of that company for permission to publish some of the data contained herein.

Hunting Airborne Geophysics Limited have kindly permitted publication of part of the data for Figure 19. Mr. D. G. MacKay and Dr. Norman Paterson were particularly helpful in this respect.

Crossland Licensing Corporation Limited, owners of the pending patent rights on AFMAG, have furnished some of the data for this paper and approved its publication.

Mr. Robert G. Lee assisted in presentation of the drawings and editing the manuscript.

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COMMENTS ON "AFMAG-AIRBORNE AND GROUND" BY S. H. WARD

Dr. S. H. Ward has kindly shown me the manuscript of the preceding paper and has invited me to comment on the origin of the natural audio-frequency

signals used by his AFMAG system. He lists five possible sources of signals. Of these, the only natural sources of practical importance in the frequency range under consideration are lightning strokes. Man-made noise may be important in the vicinity of cities or industrial areas.

Dr. Ward correctly states that signal attenuation is greater during the day in the presence of the D region of the ionosphere than at night when the D region disappears. This leads to a characteristic diurnal variation of signal strength with larger amplitudes at night than during the day provided that the frequency band used is above 100 cps and provided that there is no large area of thunderstorm activity within roughly 3,000 miles of the receiving station. Figure 3 is a good illustration of the effect of relatively close thunderstorm activity on the simple diurnal oscillation described above. After the nighttime maximum, the received signal strength decreases in part, at least, due to the development of the D region after sunrise. Instead of remaining at a low value throughout the day, the signal strength once more rises shortly before noon due to the development of the usual summer thunderstorms in the eastern part of the North American continent. The record shows a secondary maximum in the afternoon hours when North American thunderstorm activity is at its peak. As storm activity in the mid-continent subsides, there is a rapid drop in signal strength to a minimum (marked A) close to local sunset. With the disappearance of the D region the curve once more rises toward its nighttime maximum. I do not believe that there is evidence to support the interpretation of the embayment A as an increase in signal attenuation around sunset.

It is interesting to note that the "normal" diurnal pattern described above disappears if the frequency range lies between 5 and 100 cps. The signal attenuation, of the order of 1 db per 1,000 km at 100 cps becomes even lower as the frequency decreases and signals in this range are received from lightning strokes in all parts of the world. For the special case of a receiving station nearly 90 degrees from the nearest thunderstorm region, the mean signal amplitude is roughly proportional to the total number of thunderstorms in progress over the world. This leads to a diurnal oscillation on universal rather than local time. The maximum occurs near 20 hours U. T. and the minimum near 4 hours U. T. On the North American Continent, the phase of the diurnal oscillation below 100 cps is nearly opposite the normal local time oscillation.

My criticisms of the interpretation of the typical signal records do not, of course, extend to Dr. Ward's most ingenious development and use of the AFMAG system.

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University of California
Los Angeles, California

AUTHOR'S REPLY*

Dr. Holzer's comments are very appropriate and much appreciated.

The interpretation of diurnal variations of field strength is often subject to certain speculations. Dr. Holzer's extensive work in this field has minimized the speculations necessary, so that his interpretation of Figure 3 would sound more logical than my own.

However, in interpreting any such records it is absolutely essential that the effect of instrumentation on the recorded variations be appreciated fully. For the diurnal records produced in this report, an instrument with a time constant of the order of six seconds was employed. Widely separated individual bursts of energy might be smoothed from the record entirely. Thus during the time of embayment *A* of Figure 3 there might well have been some substantial local activity producing pulses more widely separated than those occurring earlier during the day.

In one recent example, obtained subsequent to writing this paper, a very local thunderstorm, involving largely "sheet" lightning, produced a record with a decrease similar to embayment *A* for the duration of the storm. Presumably in this latter event, the increased ionization of the very local atmosphere led to attenuation of signals from sources more than a very few miles away. At the same time the long time constant of the instrument removed any obvious indication of the individual lightning flashes occurring overhead. Speculating still further one might assume that had the lightning been largely of the "fork" type, then the attenuation might not have been so evident since ionization possibly would not have been so all pervading locally.

Provided one is prepared to so speculate, then an explanation for embayment *A*, similar to that originally given, may yet be valid. However, I am now inclined to favor Dr. Holzer's explanation.

Finally, it should be borne in mind that narrow-band, tuned coils and amplifiers were employed for the records contained in this paper. Thus these records should not be compared directly with records obtained with broad-band equipment.

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GEOPHYSICS, VOL. XXIV, NO. 4 (OCTOBER, 1959), PP. 790–816, 16 FIGS.

INDUCED POLARIZATION, A STUDY OF ITS CAUSES*

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ABSTRACT

The causes of induced electrical polarization include not only the polarization of metal-solution interfaces, but also effects associated with the coupling of different flows. Electro-osmotic, thermal electric, and ion diffusion effects are among such examples. A study of the physical properties of geologic materials indicates that only electrode interface and diffusion flow phenomena are important sources of induced polarization effects.

It was attempted to find characteristic differences between these two phenomena. Theoretical and experimental considerations show that the kinetic processes involved are quite similar in the two cases. This leads to difficulties in identifying the polarizing agent from electrical measurements, although the effects of well mineralized zones are easily recognized.

INTRODUCTION

During the past ten years an increasing interest has developed around the geophysical applications of electrical measurements that go under the popular name of induced polarization measurements.[1] The primary motivation has been the application of these measurements to the detection of sulphide mineralization. It is believed that the phenomenon taking place when electric current passes through a mineralized zone is essentially the same phenomenon that occurs at a polarized electrode (Bleil, 1953).

A polarized electrode is one that hinders the flow of electric current between the electrode and the solution in which it is immersed. Chemical or electrochemical barriers exist which the current carriers must overcome in order to allow current flow to pass across the electrode-liquid interface. Forcing a net current flow to take place across this interface entails an added voltage drop above and beyond that needed to overcome the ohmic losses in the solution and in the electrode. This additional voltage is called the overvoltage.

The picture that is used to explain the induced polarization effects in mineralized rocks involves the ionic current flow in the rock polarizing the metal particles within the rock. When the inducing current is turned off, the overvoltages that were set up fall off with time. Since it also takes a finite time to build up these overvoltages, one finds that the impedance of these zones decreases with increasing frequency, so that the measurements can also be made in the frequency domain. Qualitatively then, these effects behave somewhat as the ordinary

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[1] The term induced polarization is perhaps a poor one, because it has so many different connotations. It would be more descriptive if we used the expression, induced electrical interfacial polarization, but we shall not attempt to force such a tongue-twisting term on our fellow geophysicists. In any case the measurements involve the transient or frequency dependent electrical properties of the ground.

dielectric property of the materials. These effects, however, occur at audio and sub-audio frequencies which are much too low for the ordinary displacement currents to be of any significance. Irrespective of the origin of the phenomenon, any time dependent or frequency dependent behavior of the electrical impedance of rock materials at these low frequencies is referred to as an induced polarization effect.

INDUCED POLARIZATION MEASUREMENTS AND PARAMETERS

Before going on to the more general study of the possible causes of these effects, it seems worthwhile at this point to review some of the measurement techniques and to correlate the widely different ways of describing the observed polarization effects that are in current use. Results of field measurements will also be presented to demonstrate the usefulness of these measurements in mining exploration.

Several different techniques are used to measure these effects, and several different parameters are used to describe the results of these measurements. When the measurements are made in the time domain, it is a common procedure to turn the current source on for a period, and then turn it off for a period before starting a new cycle with opposite polarity. The voltage remaining just at the beginning of the off-period, or at some fixed interval later, is often measured and compared with the on-period voltage. The polarization is evaluated in terms of mv/volt. Another practice consists of integrating the off-period voltage. The polarization effects are then evaluated in terms of mv-sec/volt.

When the measurements are made in the frequency domain it is the usual practice to compare the impedance at some alternating frequency with that of some very low frequency which is often referred to as the dc impedance. The effect is then evaluated as a certain percentage increase in the conductance at the ac frequency. Sometimes phase shift measurements are made. These phase shifts are usually very small, of the order of one degree or less.

The significance and the interrelation of these varied parameters can be better understood if the ideas used to describe the polarization of a mineralized zone are transcribed into an equivalent circuit (see Figure 1).

In Figure 1, R' stands for the impedance of the complete rock section. It is made up of unblocked ionic conduction paths, R, in parallel with other paths, Z, which are blocked by metallic or semi-conducting minerals. R_m stands for the resistance of the electronic conducting minerals, and R_e stands for the resistance of the electrolytes in the blocked pore paths. C is the electrode capacitance and R_{ohem} represents the hindrance to the transfer of electrons between the metallic mineral and the solution.

Because time and frequency domain data are related to each other, when the phenomenon is linear, through the Fourier transform, we can expect to derive frequency information from the transient measurements or vice versa. There is not an exact one to one correspondence between a point in the frequency domain,

and a point in the time domain, but there is often an approximate one. The percentage frequency effect and the mv/volt parameters are found to be closely related (Madden and Marshall, 1958). If the percentage decrease in impedance is used instead of the percentage increase in conductivity, the relationship is given as percent effect at frequency $f_i \cong 0.1$ mv/volt value at $t_i = 1/2\pi f_i$.

The integrated decay voltage is a little different. It is not unlikely that $R_{chem} \gg R_m + R_e$, so that the dc impedance of $Z = Z(0)$ is approximately equal to R_{chem}. If we make this assumption, and if the integration is carried out long enough, we have that the mv-sec/volt value $= 1{,}000$ CR.

In all these parameters we have a large role played by R, the resistance of the unblocked paths. Small values of R can short circuit the polarizing effects,

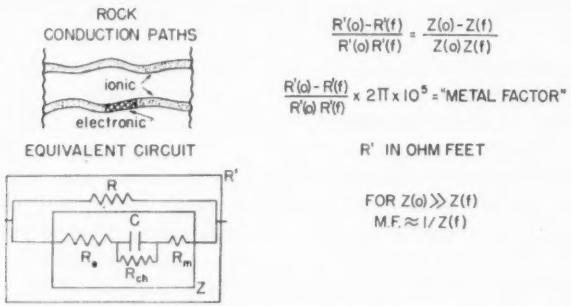

FIG. 1. Diagrammatic representation of section of conducting paths in rock, and the equivalent circuit.

resulting in very small parameter values, while a very tight rock may give large frequency effects without many metallic minerals being present. Since R is in parallel with Z it would seem advisable to look at the change in conductivity of R', for this is just the change in conductivity of Z. When the measurements are made in the frequency domain, this is simply done, and is equal to the frequency effect divided by the dc resistivity. To give reasonably sized values, this parameter is defined as $2\pi[R'(0)-R'(f)]\times 10^5/R'(0)R'(f)$ when using units of ohm-feet for the resistivity. It is called the "metal factor" because of its correlation with metallic mineral content. Using the assumptions previously mentioned concerning the parameters of Figure 1, the metal factor, m.f. $\cong 2\pi \times 10^5/Z(f)$, and is therefore proportional to the ac conductivity of those paths that are blocked off by metallic minerals. The more metal a rock contains, the more paths that will be blocked, and thus the higher the metal factor. As the metallic content continues to increase, the individual paths will have higher ac conductivities, and this two-fold effect starts to skyrocket upwards the values of the metal factor. This is helpful in increasing the signal-to-noise ratio between

the effect of well mineralized zones, and the effect of only slightly mineralized zones. This parameter does favor the rocks having conductive electrolytes in the pores, and thus it is not quite so useful when dealing with sedimentary rocks.

Some typical metal factor values evaluated at 10 cps encountered in igneous areas are shown in Table I.

Similar parameters can be evaluated from the transient measurements. The only one that seems to be used is derived by dividing the mv-sec/volt value by the resistivity. This parameter is essentially proportional to C, the interfacial capacitance per unit cube, but is more often referred to as the effective zero frequency dielectric constant. The frequency measurements could also be evaluated in terms of an effective dielectric constant, but we specifically wish to avoid the

TABLE I

COMMON METAL FACTOR VALUES (10 cps)

Rock Type and Mineralization	Metal Factors
unmineralized granites	<1
unmineralized basic rocks	1–10
finely disseminated sulphides	10–100
disseminated sulphides (1–3%)	100–1,000
fracture filling sulphides (3–10%)	1,000–10,000
massive sulphides	>10,000

use of the term dielectric constant in describing these effects. First of all this so-called effective dielectric constant is not constant, but varies widely as a function of frequency. Secondly, the huge values obtained at low frequencies seem to imply a rather anomalous dielectric phenomenon, while actually the only really anomalous phenomenon is associated with the resistive properties. The interfacial capacitance C is quite large, being of the order of 30 $\mu f/cm^2$, but is not anomalous since the interfacial layer is so thin. The anomalous feature of this layer is its high resistance, despite the fact that it is very thin. If it were not for this high resistance, the interfacial capacitance, which is no different from the capacitance of a similar thickness of ordinary fluid, would play no role.

In the remainder of this paper the polarizing effects will be referred to the frequency domain, and we shall speak of percentage frequency effects and metal factors.

FIELD RESULTS

The increased resolving power of induced polarization measurements over ordinary resistivity measurements in detecting sulphides is demonstrated by some field examples shown in Figures 2–7. The data were taken using 100 ft dipoles for both the sender and receiver. The data are plotted with the abscissa representing the separation between sender and receiver, and the ordinate repre-

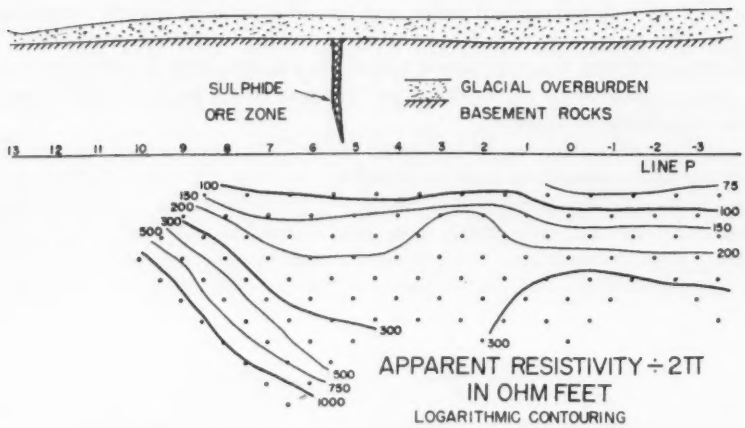

FIG. 2. Resistivity measurements using colinear dipoles.

senting the center position of the spread. In this way a sort of cross-section of the measured apparent electrical parameters are presented. Of course it is not an exact mapping, but it bears certain similarities (Hallof, 1957). The actual measured values have not been shown, merely being represented by dots, but the contours of these values are drawn in. In all these examples there is a clear cut advantage to the induced polarization measurements.

The frequency spectrum of these induced polarization effects are spread out smoothly enough so that the impedance, even though varying with frequency, remains almost purely resistive at any one frequency. This allows one to use

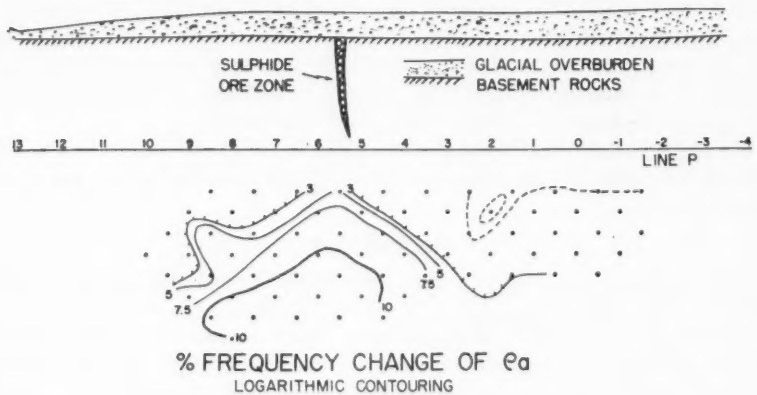

FIG. 3. Frequency variations of apparent resistivity at 60 cps.

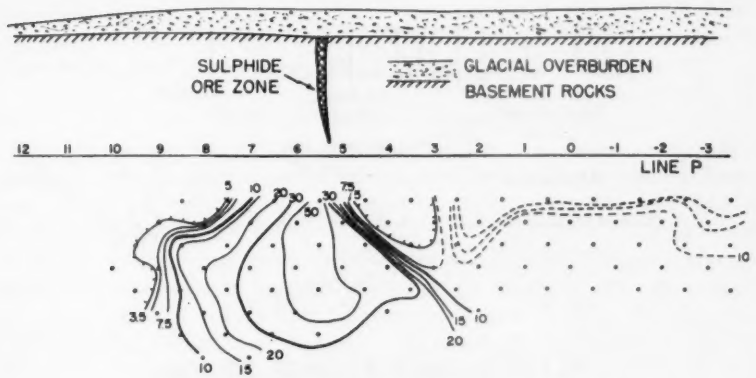
SULPHIDE
ORE ZONE
GLACIAL OVERBURDEN
BASEMENT ROCKS
12 11 10 9 8 7 6 5 4 3 2 1 0 -1 -2 -3
LINE P
APPARENT METAL FACTOR MAP (f=60~)
LOGARITHMIC CONTOURING

FIG. 4. Metal factor values computed from field measurements.

ordinary resistivity type curves to predict or interpret the apparent polarization effects of a given zone (Hallof, 1957).

COMPLICATIONS TO THE SIMPLE THEORY

The application of induced polarization measurements to the detection of sulphide mineralization is not as simple as it has been assumed in the previous discussion. One reason, of course, is that other semi-conducting minerals such as graphite, magnetite, and pyrolusite cause similar polarization effects. Polari-

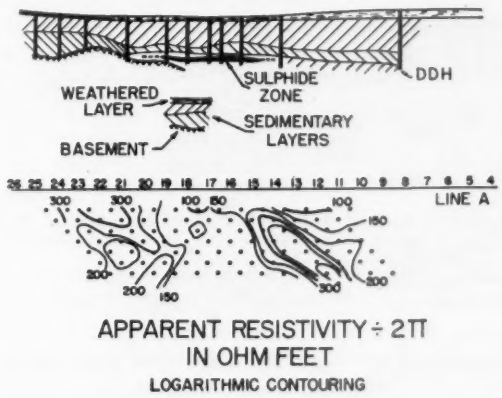

FIG. 5. Resistivity measurements using colinear dipoles.

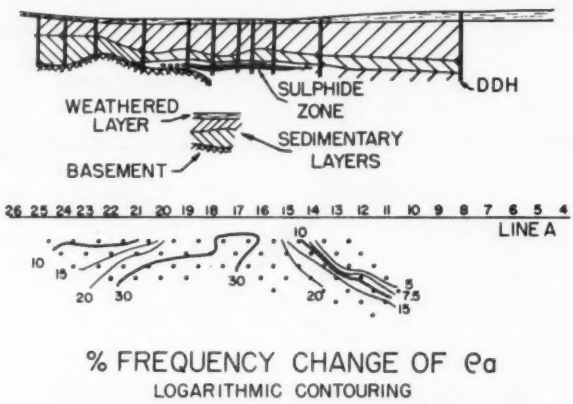

FIG. 6. Frequency variations of apparent resistivity at 60 cps.

zation can also occur, however, without the presence of any semi-conducting minerals. Schlumberger, in perhaps the first reference to induced polarization methods, stated that background polarization effects drowned out the effect of the sulphide minerals (Schlumberger, 1920). This view is somewhat exaggerated, but Vacquier in his work showed that clay minerals could lead to finite polarization effects (Vacquier et al., 1957). Other groups have also been observing these effects (Henkel and Van Nostrand, 1957; Brant, personal communication).

Because of the presence of these complicating factors, this present study was taken up. It was hoped that through an increased understanding of the causes of induced polarization in geologic materials, one could better interpret the electri-

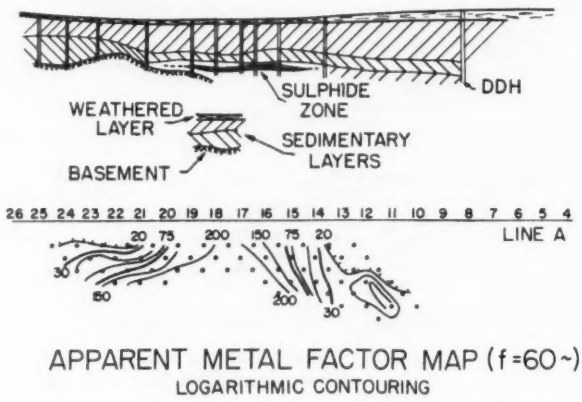

FIG. 7. Metal factor values computed from field measurements.

cal measurements. It seems appropriate then to attack this problem from a fresh point of view, starting with more general concepts rather than a specific model such as that given in Figure 1.

POLARIZATION AS ENERGY STORAGE

The observation that we have is that the polarizable materials are capable of maintaining, for a certain time, an electric current flow after an applied current field is turned off. Actually what is observed is a voltage gradient, and this does not guarantee that electric current is flowing, as will be apparent later, but some sort of flow will be taking place. This is a manifestation that energy is stored in the medium when current is passed through, and usually at least some of this energy is released by maintaining electric current flow after the driving field is turned off. The five ordinary forms of energy storage are, electric, magnetic, mechanical, thermal, and chemical. It is conceivable that any one or all of these are involved in the phenomenon. The picture presented in Figure 1 assumed that the energy was stored as electric energy in the capacitor C. This is the simplest and most direct form of setting up an electric polarization effect.

Another obvious form of energy storage is in the magnetic field. It is known that an electric current always sets up a magnetic field, and that when the current is turned off, the collapsing magnetic field returns its stored energy back into electrical energy. This effect can be very complicated when the geometry of the current flow is irregular, but for simple half-space geometries the solutions are well known (Sunde, 1949). When colinear spreads are used to make the field measurements, these electromagnetic effects behave qualitatively much like the polarization effects of mineralized zones. A two-fold increase of apparent conductivity takes place as the frequency is increased. The frequencies at which the effect is observed, however, are usually quite high, unless large separations in conductive areas are involved. For a separation of 2,000 ft in an area whose resistivity is 300 ohm-ft, no appreciable effect is observed until frequencies of 10 cps or higher are used. When the ground conductivities are not homogeneous, the electromagnetic effects can become quite different. This is especially true when horizontal variations of conductivity exist. Measurements have been made in the field where the apparent resistivity increased by more than three fold as the frequency was increased (Madden et al., 1957). These effects are again limited to the higher frequencies, however.

POLARIZATION THROUGH THE COUPLING OF FLOWS

The electromagnetic effects can be avoided, as has been mentioned, by using low enough frequencies, but anomalous polarization effects are still found when low frequencies are used. The possible effects of mechanical, thermal, and chemical energy storage must be investigated therefore. To store energy in these forms, a coupling must exist between the electric current flow and other flows such as heat and matter. The existence of such a coupling will then allow the stored

energy on its release to cause electric current flow again, and thus the phenomenon will be a form of induced electric polarization. A simple illustration of this idea is given in Figure 8. For instance, through electro-osmotic coupling, an electric current flow will cause a solvent flow through a capillary system. This flow may build up a hydrostatic pressure, either by building up a hydrostatic head against gravity, or perhaps through the blocking action of an impermeable bed. When the electric current is turned off, the hydrostatic pressure built up will drive the solvent back, and the solvent flow in turn will cause an electric current flow.

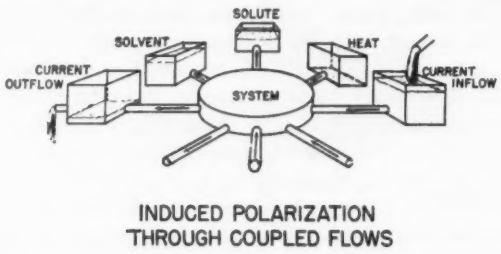

FIG. 8. Pictorial representation of the coupling of flows and the development of counter forces in a system.

This flow almost immediately builds up an electric potential which opposes any further current flow, and which is observed as a polarization voltage.

In a similar way any heat flow induced by the current flow can store energy thermally if temperature differences are set up. The solute flow can cause concentration differences to build up, and this represents a chemical energy.

The study of such couplings and their interrelations is the main area of investigation of steady-state thermodynamics. According to the principles of steady-state thermodynamics, the equations describing a general electrolyte system with coupling are[2]

$$\begin{matrix}\text{flow cations} \\ \text{flow anions} \\ \text{flow solvent} \\ \text{flow heat}\end{matrix} = \begin{bmatrix} J_p \\ J_n \\ J_s \\ J_q \end{bmatrix} = \begin{bmatrix} L_{11}L_{12}L_{13}L_{14} \\ L_{21}L_{22}L_{23}L_{24} \\ L_{31}L_{32}L_{33}L_{34} \\ L_{41}L_{42}L_{43}L_{44} \end{bmatrix} \begin{bmatrix} -\nabla\mu_p - FZ_p\nabla\phi \\ -\nabla\mu_n - FZ_n\nabla\phi \\ -\nabla P \\ -\nabla T/T \end{bmatrix} \tag{1}$$

where

ϕ = electric potential; μ = chemical potential; P = pressure;
T = temperature; $L_{ij} = L_{ji}$; F = Faraday's constant; and Z = ion valence.

[2] This is not the form of these equations usually found, but we follow Eckart here in an attempt to avoid the presence of arbitrary potential terms that appear in the formulations given in Denbigh and DeGroot (Eckart 1940, Denbigh 1951, DeGroot 1952).

The column on the left represents the flow vectors, while the column on the right of (1) represents the generalized forces. The L_{ij} matrix consists of the terms relating to the properties of the media such as the conductance and permeability.

These relationships assume a linear behavior of the medium, and this is always observed for small-flow densities. Onsager's relationships, $L_{ij}=L_{ji}$, is based on extensions of thermodynamics to situations involving slight deviations from equilibrium. It also appears to be verified experimentally for small-flow densities. This relationship is of great help in organizing the experimental results.

From these relationships the possible magnitudes of electrical polarization can be deduced in terms of the coupling coefficients. Many of these coefficients are well known from other studies. For instance, the solvent-electric current flow coupling known as electro-osmosis or streaming potential has been studied by geophysicists because of the effects on self-potential logging (Wylie, 1955). The soil mechanics engineers also have made such studies because of the possible applications in soil consolidation (Casagrande, 1952).

The thermo-electric properties are not as well known, although at present a great effort is being made to develop efficient thermo-electric materials because of their possible use in energy conversion. The measure of this efficiency is exactly the same parameter that evaluates its induced polarization capabilities. These studies are concentrating on semi-conducting materials. It is quite apparent, from data to be shown later, that geologic materials do not have the required properties.

The coupling effects between solute flow and electric currents are also very well known, being an important part of the subject matter of electro-chemistry. These effects are familiar to geophysicists using self-potential measurements, for they are represented by the familiar diffusion potential phenomena.

ELECTRO-OSMOTIC COUPLING

To investigate the possible influence of electro-osmotic coupling on induced electrical polarization we can rewrite equation (1), assuming that all the induced forces except ∇P are zero, and ignoring any dependence of μ on pressure. We also combine J_p and J_n to give us the current flow I.

$$I = F(Z_pJ_p + Z_nJ_n) = -F^2[L_{11}Z_p^2 + L_{22}Z_n^2 + (L_{12} + L_{21})Z_pZ_n]\nabla\phi - F(L_{13}Z_p + L_{23}Z_n)\nabla P \tag{2}$$

$$J_s = -F(L_{31}Z_p + L_{32}Z_n)\nabla\phi - L_{33}\nabla P. \tag{3}$$

In the ultimate steady-state a hydrostatic pressure will build up to prevent any further electro-osmotic solvent flow. The pressure gradient needed to prevent the solvent flow can be calculated from (3) by setting $J_s=0$. When this pressure gradient is introduced into (2) we obtain, using Onsager's relationship $L_{ij}=L_{ji}$,

$$I(\text{steady-state}) = -\left\{F^2[L_{11}Z_p^2 + L_{22}Z_n^2 + (L_{12} + L_{21})Z_pZ_n] - \frac{F^2(L_{13}Z_p + L_{23}Z_n)^2}{L_{33}}\right\}\nabla\phi. \tag{4}$$

The term multiplying $-\nabla\phi$ is the effective conductivity in the steady-state, σdc. If high frequencies are used, no pressure gradient can build up, and from (2) we have that the high frequency conductivity is

$$\sigma_{ac} = F^2[L_{11}Z_p^2 + L_{22}Z_n^2 + (L_{12} + L_{21})Z_pZ_n]. \tag{5}$$

The maximum frequency effect is given by

$$\frac{\sigma_{ac}}{\sigma_{dc}} = \frac{1}{[1 - F^2(L_{13}Z_p + L_{23}Z_n)^2/\sigma_{ac}L_{33}]}. \tag{6}$$

The coefficients used are not the parameters in common usage. The streaming potential, which represents the potential induced by an applied pressure gradient, can be given in terms of these same coefficients, however.

$$\left(\frac{\nabla\phi}{\nabla P}\right)_{I=0} = \xi = -F(L_{13}Z_p + L_{23}Z_n)/\sigma_{ac}. \tag{7}$$

Thus it is possible to rewrite (6) as

$$\frac{\sigma_{ac}}{\sigma_{dc}} = 1\Big/\left[1 - \frac{\xi^2\sigma_{ac}}{L_{33}}\right]. \tag{8}$$

The maximum polarization effect can, therefore, be determined in terms of the conductivity, the permeability, and the streaming potential, which are all easily measured parameters. In Table II are given some results of such measurements on geologic materials.

TABLE II

MEASURED ELECTRO-OSMOTIC COUPLING COEFFICIENTS AND POSSIBLE POLARIZATION EFFECTS

Sample	Streaming Potential mv/atm.	Maximum % Frequency Effect	Investigator
quartz s.s.	8	.03	Kermabon
quartz s.s.	9	.0002	Kermabon
red s.s.	5.5	.02	Kermabon
shale	1	.05	Kermabon
limestone	2	.03	Kermabon
kaolinite (dispersed, Na)	30	2.0	Olsen
kaolinite (natural flocculated, Ca)	17	.02	Olsen
kaolinite (flocculated, .1 N NaCl)	0.7	.007	Olsen

The values listed in the table indicate that the electro-osmotic effects are relatively unimportant in causing induced electrical polarization.

THERMO-ELECTRIC COUPLING

A very similar analysis can be carried out to investigate the possible influence of thermo-electric effects. The thermo-electric coupling is more complicated because of the role played by the chemical potentials, which depend both on the temperature and on the concentration of the solute. In general, unlike the electro-osmotic case, to evaluate the polarization contribution it would be necessary to measure both cross-coupling effects; the thermally induced potential gradients and the electrically induced thermal gradients.

If we ignore pressure effects

$$\nabla\mu_j = \frac{\partial\mu_i}{\partial T}\nabla T + \sum_j \frac{\partial\mu_i}{\partial C_j}\nabla C_j.$$

The time scale for heat flow at ordinary temperatures is much shorter than the time scale for diffusion flow, so that for certain time scales we can assume the concentrations remain unchanged. This allows us to set

$$\nabla\mu_i \cong -S_i\nabla T = -TS_i\frac{\Delta T}{T} \tag{9}$$

S_i = partial molal entropy.

Our thermal coupling equations can then be written as

$$I = F(Z_pJ_p + Z_nJ_n) = -F^2[Z_p^2L_{11} + Z_n^2L_{22} + Z_pZ_n(L_{12} + L_{21})]\Delta\phi$$
$$- F[L_{14}Z_p + L_{24}Z_n - (Z_pL_{11} + Z_nL_{21})TS_p - (Z_nL_{22} + Z_pL_{12})TS_n]\frac{\nabla T}{T} \tag{10}$$

$$J_Q = -F[Z_pL_{14} + Z_nL_{24}]\nabla\phi - [L_{44} - L_{41}TS_p - L_{42}TS_n]\frac{\nabla T}{T}. \tag{11}$$

The quantity $-F[Z_pL_{14}+Z_nL_{24}]\nabla\phi$ appearing in (11) can be interpreted as the heat transported by the ions moving under the influence of the electrical field.

$$-F[Z_pL_{14} + Z_nL_{24}]\nabla\phi = Q_pJ_p + Q_nJ_n. \tag{12}$$

Q = heat of transport.

From the definition of transference number,

$$\tau^+ = FZ_pJ_p/I; \qquad \tau^- = 1 - \tau^+ = FZ_nJ_n/I$$

we have therefore

$$FZ_pL_{14} = Q_p\tau^+\sigma_{ac}/FZ_p \tag{13}$$

$$FZ_nL_{24} = Q_n\tau^-\sigma_{ac}/FZ_n. \tag{14}$$

We also have from (10)

$$F(Z_pL_{11} + Z_nL_{12}) = \tau^+\sigma_{ac}/FZ_p \tag{15}$$

$$F(Z_nL_{22} + Z_pL_{21}) = \tau^-\sigma_{ac}/FZ_n. \tag{16}$$

A further simplification of notation is achieved by setting

$$[L_{44} - TS_pL_{41} - TS_nL_{42}] = TK; \qquad K = \text{thermal conductivity.} \tag{17}$$

We can now rewite (10) and (11), using Onsager's relation $L_{ij}=L_{ji}$, as

$$I = -\sigma_{ac}\nabla\phi - \left[(Q_p - TS_p)\frac{\tau^+}{FZ_p} + (Q_n - TS_n)\frac{\tau^-}{FZ_n}\right]\sigma_{ac}\frac{\nabla T}{T} \tag{18}$$

$$J_Q = -\left(Q_p\frac{\tau^+}{FZ_p} + Q_n\frac{\tau^-}{FZ_n}\right)\sigma_{ac}\nabla\phi - K\nabla T. \tag{19}$$

In the steady-state limit $J_q=0$, and solving for the temperature gradient set up we can obtain the steady-state conductivity.

$$\sigma_{dc} = \sigma_{ac}\left[1 - \frac{\left(\sum Q_i\frac{\tau_i}{FZ_i}\right)\left(\sum (Q_i - TS_i)\frac{\tau_i}{FZ_i}\right)\sigma_{ac}}{TK}\right]. \tag{20}$$

If the time scale is extended, the temperature gradients can also establish concentration gradients (Soret effect) which will modify the current flow because of the diffusion potentials set up. A greater practical difficulty in establishing the magnitudes of these effects is the fact that a measurement of the thermo-electric coefficient

$$\theta = \left(\frac{\nabla\phi}{\nabla T}\right)_{I=0} = -\sum\left(\frac{Q_i - TS_i}{T}\right)\frac{\tau_i}{FZ_i} \tag{21}$$

is not enough to establish the polarization effects of this coupling. In principle one would need to also measure the heat of transport. Such a calorimetric measurement is much more difficult to carry out than the electrical measurement involved in (21).

We can make estimates of the term $\sum Q_i(\tau_i/FZ_i)$ in (20) which are adequate for our purposes here. In most rocks the positive ion transference number is much larger than the negative ion transference number. Thus

$$\theta \cong \frac{Q_p - TS_p}{TFZ_p}. \tag{22}$$

The partial molal entropies for aqueous solutions of ions are known, so that if we can assume similar values for the ions in the pore fluids, (22) would give us an estimate of $\sum Q_i(\tau_i/FZ_i)$. Using KCl solutions typical values of θ ran around 0.3 mv/deg.C. These were measured in a cell where the thermo-electric voltages across the rock samples were bucked against the thermo-electric voltage across a water column (Uhri, 1958). The voltage between the measuring electrodes were then corrected for a semi-theoretical value of the water thermo-electric voltage (Eastman, 1928, and Wirtz, 1948). The partial entropy value for K^+ of 24 entropy units per mole, thus gave from (22) an estimate of Q_{K+} of 3.6 Kcal/mole. The value of $\sum(Q_i - TS_i)\tau_i$ was about 2.3 Kcal/mole, so that we are within the correct order of magnitude to replace $\sum Q_i\tau_i$ by $\sum(Q_i - TS_i)\tau_i$. This allows us to rewrite (20) as

$$\frac{\sigma_{ac}}{\sigma_{dc}} \cong 1 \Big/ \left(1 - \frac{T\theta^2\sigma_{ac}}{K}\right). \tag{23}$$

In Table III are listed some of the thermo-electric data and the approximate maximum polarization effect possible from such coupling.

TABLE III

MEASURED THERMO-ELECTRIC COUPLING COEFFICIENTS AND POSSIBLE POLARIZATION EFFECTS

Sample	Thermo-Electric Coef. mv/deg. C	Maximum % Frequency Effect
ss. with clay	.23	.000003
s.s.	.48	.00003
shale	.33	.00004
limestone	.27	.0000002

It is obvious that this coupling is of no importance in causing polarization effects. Actually the thermo-electric coefficients are quite high, but the ratio of electrical conductivity to thermal conductivity is very low, so that from (23) $\sigma_{ac} \cong \sigma_{dc}$. This is also the reason why semi-conductors are being used for thermo-electric power conversion; one must have a very good electrical conductor as well as strong thermo-electric effects.

DIFFUSION COUPLING

It is apparent by now that the cross terms appearing in the matrix describing the flow properties of the medium are not large enough in geologic materials to cause appreciable polarization effect. It is quite a different matter, however, when diffusion flow effects are investigated. This, of course, is because the ions themselves carry the electric current, so that the diffusion gradients and the electrical potential gradients have to appear together as primary driving forces for the ion motion.

If we drop all the off diagonal terms in (1) we are left with

$$J_p = - L_{11}\nabla\mu_p - L_{11}FZ_p\nabla\phi \tag{24}$$

$$J_n = - L_{22}\nabla\mu_n - L_{22}FZ_n\nabla\phi \tag{25}$$

as the flow equations for the anions and the cations. In place of the coefficients L_{ij}, we can introduce the more familiar electrochemical quantities of mobility, diffusion coefficients, and transference numbers. Thus we can rewrite the flow equations, assuming uni-valent ions, as

$$J_p = - D_p \frac{\partial p}{\partial x} + u_p pE \tag{26}$$

$$J_n = - D_n \frac{\partial n}{\partial x} - u_n nE \tag{27}$$

U = mobility — p = cation concentration

D = diffusion coef. — n = anion concentration

$t^+ = U_p/(U_p + U_n) = D_p/(D_p + D_n)$ = cation transference no.

$t^- = 1 - t^+$ = anion transference no.

If t^+ should vary along the current path, a divergence will result in the flow of the ions, causing concentration gradients to build up. This is illustrated in Figure 9 where zone II represents a strongly cation selective zone, and zone I represents a zone with no selectivity. Because of its selective transference properties zone II would be called a membrane zone. Since the current in zone II is largely carried by the cations, a surplus of these ions will occur at one end of zone II, and a deficiency at the other end. The anion flow will also be unbalanced, and the buildup of anions will equal that of the cations. The resulting concentration gradients will modify the ion flow until a balance is reached. In this steady-state

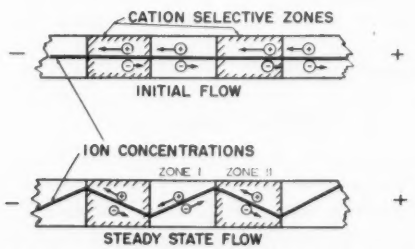

FIG. 9. Ion motion and concentration changes developed by current flow through a membrane system.

condition the net flow of cations and anions in zone II will equal that in zone I.

$$J_{p\mathrm{I}} = J_{p\mathrm{II}} \tag{28}$$

$$J_{n\mathrm{I}} = J_{n\mathrm{II}}. \tag{29}$$

The impedance of the zones will also be modified, because the concentration gradients developed will have diffusion potentials associated with them. These potentials arise because of a slight unbalance of charge , but since so little charge is needed to develop an electric field, one can say that the cation and anion concentrations are essentially equal.

$$p = n. \tag{30}$$

The electric field is assumed to be constant in each zone, so that the total potential difference across the pair of zones is given by

$$\Delta\phi = -E_{\mathrm{I}}\Delta L_{\mathrm{I}} - E_{\mathrm{II}}\Delta L_{\mathrm{II}}. \tag{31}$$

The concentrations, p and n, will be continuous across the boundaries, so that if the succeeding zones repeat the same pattern with the same geometry and electrical properties, we can put

$$\Delta p_{\mathrm{I}} = -\Delta p_{\mathrm{II}} \tag{32}$$

$$\Delta n_{\mathrm{I}} = -\Delta n_{\mathrm{II}}. \tag{33}$$

When it is also assumed that the concentration gradients are constant in each zone, (28), (29), (30), (32), and (33) can be considered as a system of algebraic equations for the unknown electric fields and concentration gradients. Solving these we obtain for the steady-state conductance

$$\sigma_{\mathrm{dc}} = \frac{Fu_{p\mathrm{I}}C\left(\dfrac{1}{\tau_{\mathrm{II}}^{-}} + \dfrac{A}{B}\dfrac{1}{\tau_{\mathrm{I}}^{-}}\right)S_{\mathrm{I}}S_{\mathrm{II}}}{\Delta L_{\mathrm{I}}\left[S_{\mathrm{I}}\left(1 + \dfrac{B}{A}\right) + S_{\mathrm{II}}\left(1 + \dfrac{A}{B}\right)\right]} \tag{34}$$

c = net concentration

$A = \Delta L_{\mathrm{I}}/\Delta L_{\mathrm{II}}$

$B = D_{p\mathrm{I}}/D_{p\mathrm{II}}$

$S_i = \tau_i^{-}/\tau_i^{+}$.

At the high frequency limit, no concentration gradients develop, and the only unknowns are the potential gradients. Using the condition that the electric current is the same in the two zones as well as the condition on the total voltage given by (31) allows us to solve for the conductance

$$\sigma_{\mathrm{ac}} = Fu_{p\mathrm{I}}CA/\Delta L_{\mathrm{I}}(A\tau_{\mathrm{I}}^{+} + B\tau_{\mathrm{II}}^{+}). \tag{35}$$

TABLE IV

POLARIZATION OF MEMBRANE MODEL

percent frequency effect ($\tau_I^+=0.5$)

τ_{II}^+	$B=$ / $A=$	1 / .1	1 / 1	1 / 10	3 / .1	3 / 1	3 / 10	D_P Ratio Length Ratio
.999		4.8	33	81	1.6	14	62	
.990		4.5	32	67	1.6	14	57	
.909		3.3	20	20	1.2	9.6	27	
.667		.7	2.8	1.2	1.9	1.8	2.5	

The maximum frequency effect that diffusion coupling can develop in our model is given as

$$\frac{\sigma_{ac}}{\sigma_{dc}} = \frac{(A+B)\left[\dfrac{A}{\tau_I^-\tau_{II}^+}+\dfrac{B}{\tau_I^+\tau_{II}^-}\right]}{\left[\dfrac{A}{\tau_{II}^+}+\dfrac{B}{\tau_I^+}\right]\left[\dfrac{A}{\tau_I^-}+\dfrac{B}{\tau_{II}^-}\right]}. \tag{36}$$

Typical values are given in Table IV. It will be observed that there is a finite limit to the frequency effect caused by this form of polarization.

For the time scales to be reasonable, the zones must be very small, and one would not be able to measure the electrical properties of each zone. The presence of membrane zones should make itself known when diffusion measurements are made, because the average transference value for the anions and cations will not be equal, and a diffusion potential will be set up. The information given in Table IV is therefore plotted in Figure 10 in terms of the effective transference number which would be determined from diffusion potential measurements. In Table V are shown the results of diffusion measurements on a few rock samples, and the possible polarizing effects that diffusion coupling could result in.

The values listed above show that these diffusion coupling effects are capable of causing considerable electrical polarization. There are two factors that should be pointed out here. First of all the possible polarization effects could increase without limit if we assumed that zones with positive ion blocking properties

TABLE V

MEASURED TRANSFERENCE VALUES AND POSSIBLE POLARIZATION EFFECTS

Sample	t^+ (Effective)	Maximum % Frequency Effect
tuff	.51	1
tuff	.72	40
tremolite limestone	.87	72
sandstone, medium grained	.48	1
sandstone, medium grained	.49	1
sandstone, fine grained	.89	78
dirty sandstone	.6	20

existed as well as those zones which can block negative ions. It is very unlikely that geologic materials will ever include such zones, but synthetic ion exchange resins can be found that do. The second factor that should be pointed out is the dependence of the polarization effect on the length ratio A. If a material has zones of very high t^+ values, but these zones are too numerous, so that most of the conduction path lies within such zones, little polarization will result. If has been

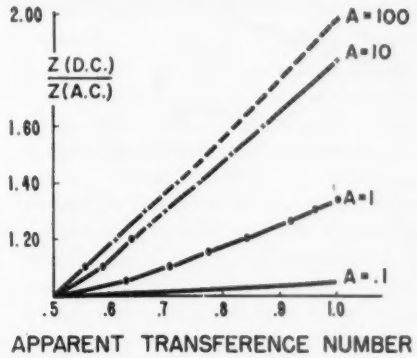

FIG. 10. Effect of the ratio of the zone lengths on the maximum polarization of a membrane system.

noted before that clays, despite their very striking t^+ values, often show extremely little polarization effect, especially if they have been mechanically manipulated. It is believed that this may be due to a tendency for the conduction paths to lie almost entirely within clay zones. Vacquier in his work reported that he could only obtain polarization effects from clays when he coated them on sand grains.

We have advanced no theory here as to why the pores of a rock or clay particles should show much membrane properties. This will involve a microscopic theory of the mineral solution interfaces. It is interesting to point out in this connection, however, that the presence of a surface charge on the minerals does not by itself cause any polarization.

A more detailed study showed that a fixed charge in a system can lead to a very slight polarization, but it is really necessary, if the system is to have a finite polarization effect, that the motion of certain ions be hindered in the system. Thus it appears that the electrostatic and Van der Waal forces that attract the positive ions to the surface of a polarizing clay system must also act to prevent negative ions from moving along the surface.

COMPARISON OF ELECTRODE AND MEMBRANE POLARIZATION

The model given for membrane polarization sets a finite limit to the polarization effect of membrane zones within a rock. The model given in Figure 1 for

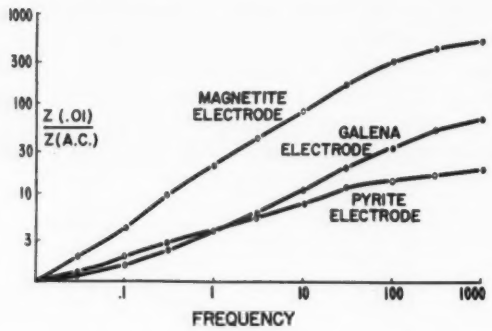

FIG. 11. Impedance of natural electrodes.

electrode polarization is not so limited however. In Figure 11 is shown some data on the interfacial impedance of a few natural electrodes. The frequency effects are much larger than 100 percent. We might expect, therefore, to find a difference between the magnitude of the observed polarization depending on the cause of the polarization. Because of the diluting, mentioned before, that is caused by parallel unpolarized conduction paths, it seems best to compare the metal factors rather than the percentage frequency effects. In Figure 12 there is shown in a somewhat generalized form, the results of laboratory measurements on a large number of rock samples, and field measurements in many areas. These results again indicate the pronounced polarization effects of well-mineralized rocks. However, in rocks with less mineralization, there begins to exist considerable ambiguity. This is especially true in sedimentary rocks of high conductivity. The geometry of the mineralization is also very critical. When the sulphides form connected veinlets

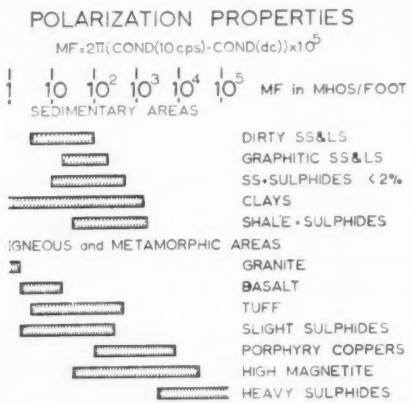

FIG. 12. Distribution of observed metal factor values.

their metal factor values are far superior to those of well-disseminated sulphides.

These results, although not eliminating the great usefulness of induced polarization measurements, do point out certain dangers in holding too simple a concept about the causes of the polarization. It also leads one to search for other criteria, besides a magnitude criterion, to help in separating out the various contributing factors.

FREQUENCY BEHAVIOR OF MEMBRANE POLARIZATION

The mechanism involved in membrane polarization appears to be quite different than that pictured in Figure 1 for electrode polarization. It might be hoped, therefore, that the details of the frequency spectrum for the two polarization effects would lead to some means of distinguishing between the different effects. For this reason the study of the membrane model was expanded.

From equations (26) and (27) we can obtain the equations of motion for the ion species.

$$\frac{\partial p}{\partial t} = D_p \frac{\partial^2 p}{\partial x^2} - U_p \frac{\partial}{\partial x}(pE) \tag{37}$$

$$\frac{\partial n}{\partial t} = SD_p \frac{\partial^2 n}{\partial x^2} + SU_p \frac{\partial}{\partial x}(nE). \tag{38}$$

Poisson's equation must also be satisfied

$$\frac{\partial E}{\partial x} = \frac{F}{\epsilon}(p - n). \tag{39}$$

These equations are non-linear but can be linearized for our case since we are interested in very small current densities. For small current densities we can consider the electric fields and the concentration changes to be small

$$\begin{aligned} P &= C + \Delta P \\ N &= C + \Delta N, \\ E &= \Delta E. \end{aligned} \tag{40}$$

If the product of these small terms is neglected and harmonic time dependence is assumed, (37), (38), and (39) become linear equations for Δp, Δn, and ΔE.

$$i\omega \Delta p = D_p \frac{d^2 \Delta p}{dX^2} - U_p C \frac{d\Delta E}{dX} \tag{41}$$

$$i\omega \Delta n = SD_p \frac{d^2 \Delta n}{dx^2} + SU_p C \frac{d\Delta E}{dx} \tag{42}$$

$$\frac{d\Delta E}{dx} = \frac{F}{\epsilon}(\Delta p - \Delta n). \tag{43}$$

These equations are the ones usually dealt with in treatments of space charge effects, and appear in discussions of solution-electrode interfaces as well as in this membrane model (MacDonald, 1953). The general solutions are simple exponentials with two characteristic lengths.

$$\begin{aligned} \Delta p &= L_p e^{\pm r_1 x} + M_p e^{\pm r_2 x} \\ \Delta n &= L_n e^{\pm r_1 x} + M_n e^{\pm r_2 x}. \end{aligned} \tag{44}$$

One of these characteristic lengths

$$\frac{1}{r_1} = 1/K\left(1 + \frac{j\omega(S+1)}{DSK^2}\right)^{1/2} \cong 1/K; \qquad K^2 = \frac{2CF^2}{\epsilon RT} \gg 1 \tag{45}$$

is essentially frequency independent and represents a space charge set up at the boundaries of a zone. The other characteristic length

$$\frac{1}{r_2} = \left[\frac{2D_p S}{j\omega(S+1)}\right]^{1/2} \tag{46}$$

varies inversely with the square root of the frequency and represents a diffusion phenomenon.

The undetermined constants in the solution are solved for by imposing the boundary conditions. In the membrane model, because of the symmetry imposed by the regular spacing of the zones, there are six constants to be determined, three for each zone. The boundary conditions can be given as the continuity of concentration and of ion flow at the boundary, the continuity of E at the boundary, and the condition that $\int \Delta E dx = -\Delta\phi$, the applied potential. These conditions, when expressed in terms of the general solutions, give us six simultaneous algebraic equations for the undetermined constants. Their solution is straightforward, but laborious, since the system of equations is highly singular and many terms must be carried along. The impedance of the membrane zone can then be determined and is given by

$$Z = \frac{\Delta L_{\mathrm{I}}}{U_{p\mathrm{I}} CF}\left\{ t_{\mathrm{I}}^{+} + \frac{B}{A}\, t_{\mathrm{II}}^{+} + \frac{(S_{\mathrm{II}} - S_{\mathrm{I}})^2}{\dfrac{X_{\mathrm{I}} S_{\mathrm{I}}}{(t_{\mathrm{II}}^{+})^2 t_{\mathrm{I}}^{+} \tanh X_{\mathrm{I}}} + \dfrac{A}{B}\,\dfrac{X_{\mathrm{II}} S_{\mathrm{II}}}{t_{\mathrm{II}}^{+}(t_{\mathrm{I}}^{+})^2 \tanh X_{\mathrm{II}}}} \right\}$$

$$\begin{aligned} X_i &= \left(\frac{j\omega}{2D_{p\mathrm{I}} t_i^{-}}\right)^{1/2} \frac{\Delta L_i}{2} \\ A &= \Delta L_{\mathrm{I}}/\Delta L_{\mathrm{II}} \\ B &= D_{p\mathrm{I}}/D_{p\mathrm{II}} \\ S_i &= t_i^{-}/t_i^{+}. \end{aligned} \tag{47}$$

Values of the membrane impedance as a function of frequency are shown in Figure 13, where it is assumed that zone I is a neutral zone. The value used for

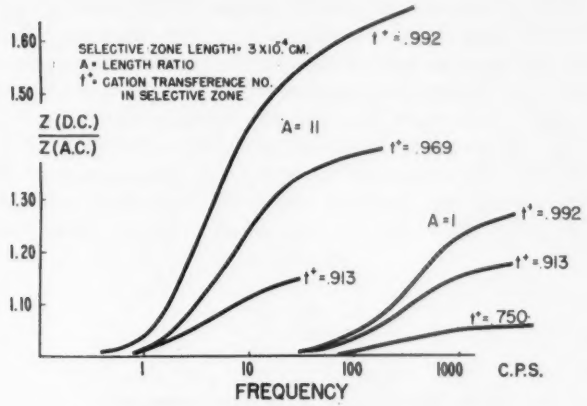

FIG. 13. Details of the impedance of a simple membrane system.

ΔL_2 of 0.3×10^{-3} cm. is typical of the size of clay particles. The frequency response for a given zone size is quite sharp. The frequencies at which the impedance is varying depend on the square of zone length, so that in an actual system with a distribution of zone lengths we can expect the frequency variations to be spread out over a wide range of frequencies. In Figure 14 are shown some impedance measurements on real membrane systems for comparison.

FREQUENCY BEHAVIOR OF ELECTRODE POLARIZATION

To compare electrode polarization to membrane polarization we must extend the simple model of Figure 1. In fact the data shown in Figure 11 are quite different from what we would expect from a simple RC circuit. Therefore, to better under-

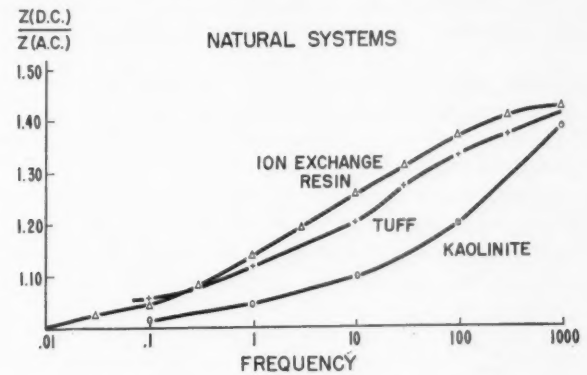

FIG. 14. Details of the impedance of a natural membrane system.

stand the nature of electrode impedances, detailed kinetic calculations were also carried out for the impedance of an electrode-solution interface. Equations (41) (42) and (43) can again be used to describe the ion motions, but the boundary conditions are very different. First of all there can be capacitive coupling between the solution and the electrode. Secondly any Faradaic current involving actual charge transfer must entail chemical reactions, and a whole chain of events may follow depending on the products of these reactions. These events are all reflected in the boundary conditions, and thus modify the electrode impedance (Madden and Marshall, 1959). When typical reaction rate values are used, however, the

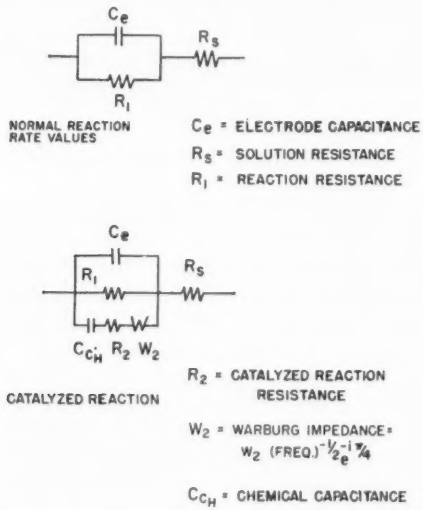

FIG. 15. Equivalent circuits for the impedance of polarized electrodes.

solutions obtained indicate that at audio and sub-audio frequencies the circuit of Figure 1 should well represent the electrode impedance. If a reaction occurring at the surface is well catalysed, a different behavior would be expected. There is little reaction resistance in such a case, but the depletion of the reacting species at the surface would require a diffusion of the ions to or away from the surface. This is responsible for an impedance which has the typical diffusion behavior and depends inversely on the square root of the frequency. It is called a Warburg impedance and is given the symbol W (Grahame 1952). The accumulation of the reaction product will in general tend to oppose any further reaction, and this causes an impedance just like that of a capacitance. We have given this capacitance the symbol C_{ch}. The equivalent circuits for an electrode impedance with normal reactions or with catalyzed reactions are shown in Figure 15.

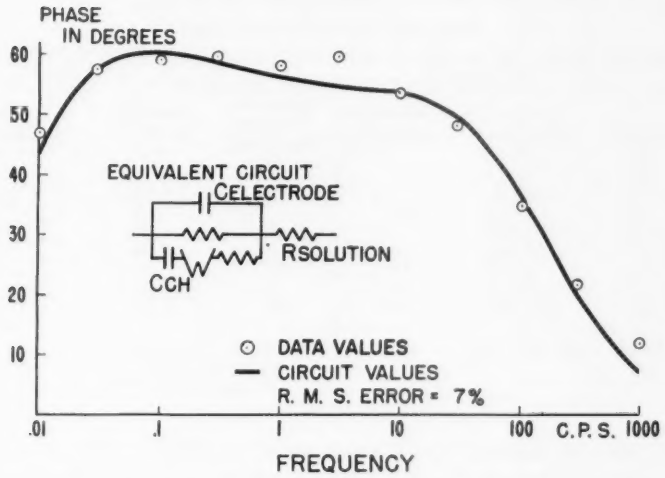

FIG. 16. Phase shift of the impedance of a magnetite electrode, and its comparison with the equivalent circuit.

Measurements were made on a wide variety of electrodes, and data were also obtained from the literature. Equivalent circuits such as those shown in Figure 15 were then adjusted to fit the data. In most cases the circuits could be made to fit the data within the experimental error. An example of such a fit is shown in Figure 16, where only the phase of the impedance is plotted. The magnitude of the impedance for this same electrode is shown in Figure 10, and on this logarithmic scale the errors of the equivalent circuit would not be discernible. The most striking result of these measurements was that in every case a well catalyzed reaction appeared to be taking place and contributed a large part of the current being passed. This means that the impedance was in a large part controlled by a diffusion phenomenon, just as in the membrane model. A summary of these electrode measurements is given in Table VI.

SUMMARY AND CONCLUSIONS

When using induced polarization measurements for the detection of metallic or semi-conducting minerals, one must be aware of other causes of the electrical polarization. An examination of the possible causes of these effects reduced the important factors to electromagnetic coupling effects and membrane polarization as well as the metallic mineral, i.e., electrode polarization that one is usually looking for. The electromagnetic effects can be avoided by using only information at very low frequencies. In typical mining exploration applications, one must work with frequencies of less than 10 cps.

TABLE VI

SUMMARY OF ELECTRODE IMPEDANCES

Values are given for 1 cm² of surface at room temp. Symbols are referred to Fig. 15.

Electrode	Reaction Resistance R_1	Electrode Capacitance C_e	Catalyzed Reaction Resistance R_2	Warburg Impedance W_2	Chemical Capacitance C_{ch}
ST steel	160,000	3.2	11	3,960	247
Ni	8,500	112	3	670	830
Cu	3,080	3.8	19	1,270	55,000
Graphite	49,500	80	26	2,700	170
Pyrite	3,900	15.	60	800	150,000
Galena*	3,800	8.5	6	760	43,000
Magnetite*	222,000	4.8	101	5,870	106

* Area not known accurately.

Resistances given in ohms.
Capacities given in μf.
W_2 calculated at 1 cps.

The effects of membrane polarization are more difficult to separate out. The effects are more limited than the electrode polarization, but may still be significant. Detailed investigations of these two processes were made to look for fundamental differences in their electrical behavior. Unfortunately the investigations showed that the principal factor contributing to the electrode impedance is a diffusion phenomenon, and this is the same factor involved in membrane polarization. Both electrode and membrane impedances show a wide and gentle frequency variation making any discrimination on this basis very difficult. This result was borne out in the measurements on rock and clay samples. The phase shifts of the metal factor, which should represent approximately the phase shift of the blocked conduction paths, were computed from an analysis of transient measurements at one tenth, one and ten cps. for hundreds of samples. Although the results were often quite characteristic for a given rock or clay type, there seemed to be no clear separation between those samples with electrode polarization and those with membrane polarization. Some typical values are shown in Table VII.

This represents of course only a somewhat limited frequency range and a wider frequency analysis might prove to be more discriminating. It is difficult, however, to extend the measurements to higher frequencies in the field because of the electromagnetic coupling effects. The measurements at lower frequencies are in principle possible, but the natural earth currents make the noise problem an important practical factor.

The magnitude of the polarization effects still appears to be the best guide for the detection of electrode polarization in rocks. When the mineralized target is well below the surface, the observed effects are, of course, considerably reduced, and may be hardly different than a small background polarization. The authors are of the opinion that the greatest improvement in interpretation will come from

TABLE VII

METAL FACTOR PHASE IN DEGREES

Sample Type	Frequency cps.		
	10	1	0.1
Kaolinite	9	14	22
Mica	8	12	19
Ion exchange resins	13	29	51
Sediments from Colorado Plateau			
with sulphides	12	20	30
little or no sulphides	9	15	21
Sedimentary copper ore	12	18	19
Rhodesian copper ore	18	27	41
Field data, porphyry copper body		18	31
Lithic Tuff, little or no sulphides	12	22	34
Graphitic ss	13	16	22
Dirty sands from Dakota, ss sequence	11	17	30
Manganese ore	9	14	22
Highly magnetic altered, ultrabasic	42	41	47

an accurate handling of this geometric factor, rather than a subtle analysis of the frequency spectrum of the observed polarization.

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All of our early work on induced polarization was done with fellow students, Phil Hallof, now at McPhar Geophysics, Keeva Vozoff, now at the University of Alberta, and Norman Ness, and their contributions are firmly entrenched throughout this paper. We also wish to acknowledge a fruitful interchange of ideas and information with Dr. A. A. Brant, whose group at Newmont Exploration Co., developed and carried out perhaps the first wide scale use of induced polarization, and Dr. Ralph Holmer and George Rogers of the Bear Creek Mining Co., whose group also has considerable field experience in these measurements. We are indebted to Hal Olsen and Professor Martin of the Civil Engineering Department for their help in carrying out and interpreting measurements on clay systems.

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FIELD TESTING SEISMIC INSTRUMENTS*

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ABSTRACT

The field tests compiled here are designed to detect the presence of the subtle as well as the obvious equipment troubles. Auxiliary test equipment used includes a low distortion sine wave oscillator, oscilloscope, geophone shaketable, and a timing standard as well as the usual voltmeter, ammeters, and ohmmeters which are often built in the equipment. Field test procedures on geophones, cables, seismic amplifier, seismic oscilloscope cameras, magnetic seismic recorders are included. The time lapse between each test is considered, but some flexibility in this respect is recognized, depending on the specific equipment used and the operating conditions.

INTRODUCTION

A secret black box philosophy surrounded seismic instruments in the early days of seismic exploration. The nature and results of instrument tests were not always available to the company paying for the seismic work. The present trend is away from this philosophy, with some seismic contractors furnishing complete circuit diagrams of their instruments, regular test records, and instrument test reports to the company employing them. Companies doing their own seismic work are also requiring their crews to complete regular field tests. In the interest of better seismic mapping, the trend toward more and better instrument tests appears highly desirable.

Small deviations in a few seismic records can mean the difference between mapping a closed structure and not mapping it. A trouble such as instability in the timing line generator can create false structures if not detected. Other troubles may cause the loss of good reflections, resulting in mapping only partial structures. Millions of dollars are at stake in drilling decisions based primarily on seismic work, so every effort to reduce instrument errors should be made.

Some of the more obvious seismic instrument troubles can be detected by careful examination of the field records. Instrument troubles which are often more serious require more detailed tests to detect. The use of a low distortion sine wave oscillator for serious distortion, automatic gain control troubles, and amplitude equalization is essential. Voltmeters, ammeters and ohmmeters are usually built in the instruments. Special equipment for testing should include a geophone shake table and a standard for checking the timing. A cathode ray oscilloscope is an optional but useful test instrument.

The purpose here is to describe some of the field tests, which can reasonably be expected of a seismic crew. These tests will be limited to field tests and will

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not include laboratory tests which are necessary to compare one seismic amplifier and recording system with another.

TESTS WITH EACH SHOT

The standard obvious checks before each shot are necessary and important if good seismic records are to be obtained and good analysis assured. A quick check of all voltages and switch positions should be made before each shot. The equipment should be warmed up and operating properly. The disc, tape, or drum speed on magnetic recorders can be observed with the meter or light on the recorder. During the signal return from the shot the overmodulation light or the modulation meter should be observed to guard against overmodulation of the magnetic medium. Extremely low level modulation can also cause trouble, since there may not be any signal left after the seismic noise is filtered out. For weight dropping operations the speed of the recorder must be accurately checked, since the summation of a large number of traces is required.

A two or three-minute examination of the seismic record after each shot can disclose some of the most obvious equipment errors or troubles in both reproducible and conventional seismic recording systems. It may be possible to check only a percentage of the records in very rapid water shooting, but normally every record should be checked. The amplitude, polarity, and clarity of the time break and uphole seismometer break should be checked. The first breaks should be checked for the use of correct presuppression and for proper polarities. The over-all record amplitude should be about the maximum possible without excessive crossovers. Severe noise in one or two amplifiers can often be found by this check. This should not be confused with low microseism noise, which is normally visible on the end of seismic records. The detection of phase shift errors on field records is largely limited to the detection of phase reversals such as reversed polarities of seismometer groups or similar large phase shifts; since weathering, noise, and other natural phenomena cause small phase shifts. Distortion can be detected on field records only if it is very severe, such as that caused by amplifier clipping and similar equipment troubles. The problem of the proper filter settings for a given area is a controversial problem, hence only a few general statements will be made. An over-all noisy record may indicate the need for lower high cut filtering. The need for a low cut filter with a steeper slope or a higher setting of the low cut filter is often indicated by a ground roll blankout region. The need for wider filtering may be indicated by smooth records (records with good reflections which lack character). Seismic records applied to a magnetic storage medium usually require no high cut filtering and only modest low cut filtering. It is usually desirable to obtain one playback record for field inspection. Special purpose traces can also be checked by field inspection. These traces may include special mixed traces, energy indicating traces, stepped gain control traces, AGC traces, amplitude calibration traces, and similar traces. Galvanometers can be checked for position and noise. When synchronous timing motors are used to

produce timing lines in the oscillographs, it is important to record a timing signal on the seismic record. Agreement between the timing lines and the timing signal should be well within $\pm\frac{1}{2}$ millisecond. Timing lines produced by the flashing light technique are somewhat less susceptible to small variation, but often do produce random lines when troubles occur. The timing signal recorded on seismic records can also be used to check timing lines in this case. The recording of a good timing signal is essential in reproducible recording, since the recorded timing signal is used to produce the timing lines on the reproduced record.

TESTS BEFORE EACH PROFILE

Resistance measurements should be made on each geophone group, and any wide variation from the normal resistance reading should be followed by a detailed check of the geophones and cable connections. A seismometer tap test should be made by tapping a geophone and recording the output on a short test record. This is usually done with all the amplifier inputs in the parallel switch position. High line 60 cycle signals can be reduced by observing the galvanometer deflection and adjusting the high line balance resistors.

DAILY TESTS

This group of daily tests is usually made in the morning just before shooting begins. Most of the troubles resulting from long drives and equipment movement can be detected in this way. The galvanometer positions may be observed by checking the galvanometer light spots, as it is usually necessary to make some small adjustments. The amplitude and gain controls on the seismic amplifiers should be set using the test oscillator and observing the galvanometer deflection or output meter. The position at the gain potentiometer and the amplitude control on each amplifier should be approximately the same. If it is necessary to adjust the gain or amplitude control to a radically different position, trouble may be present. With the presuppression tripped, the gain controls should be high enough to give a small galvanometer deflection for the microseism level. All battery and power supply voltages should be checked under normal load conditions. A battery hydrometer check is usually desirable, especially under conditions where the batteries must operate all day without recharging. The hydrometer test can be used to locate weak cells as well as estimate the time the batteries can be operated without recharging.

A sine wave oscillator test can be made with all the amplifier inputs in parallel. Normal filter and automatic gain control positions are usually used in this test; however, if there is reason to suspect the presence of noise or distortion in the seismic system, the test should be repeated with no filtering. No filtering allows noise and distortion to show up more clearly. The oscillator voltage should be varied in about ten decibel steps over the range from one microvolt to one-tenth volt. With the camera running the oscillator voltage should be varied in steps of one to ten and ten to one to check the automatic gain step control. The oscillator

used in this test should have less than four percent distortion to give a good visual indication of distortion. Distortions of less than five percent are not easily detected by eye.

A seismometer tap test can be recorded with the oscillator test. This test should include one hard tap and two or more light taps. The phase on all traces should agree within ± 1 millisecond. If amplifier noise is present it should show with the low level signal, but probably not with the high level signals. Galvanometer noise usually shows throughout the record. A magnetic recording can also be made of the test strip and played back to test the recorder.

In both of the above tests the traces should match very closely with possible exception of the very high level pulses. It is difficult to match the automatic gain control circuit diodes close enough to obtain perfectly matched traces on high level pulses.

Paper speed can be checked by measuring the timing lines. Timing check, galvanometer position check and development process checks can be made from the test record.

A few additional checks are needed if a magnetic recorder is used. The magnetic recorder heads should be checked for dirt and cleaned if necessary. Tape modulation level should be checked with test meter, using the oscillator operating through a seismic amplifier with normal automatic gain control. The output level from each magnetic recorder channel should also be adjusted to the proper level. Magnetic recorders using frequency modulation or pulse width modulation often use a pilot channel which is modulated with noise ("wow and flutter") caused by speed variation in the disc or drum drive mechanism. This signal is added to all other seismic signal channels with the proper phase to cancel out the noise produced by the speed variation. It is important to calibrate pilot channel for optimum cancellation. This can be done by recording a no input record, then playing back a regular seismic channel and adjusting the pilot channel for minimum output. The seismometer tap tests and oscillator test should be played back and a paper record made, so as to test the magnetic recorder as well as the seismic amplifiers.

Some companies are now removing normal move out and weathering from seismic records after the records have been recorded. Weathering is removed by moving the heads a fixed distance. Normal move out removal requires that the head be moved in the proper way while the record is being played back. The controls for normal move out removal vary widely and include mechanical as well as electrical controls. Special tests are required for each type. Good velocity profiles and accurate geophone group locations are essential for setting up the head movement pattern. Other variable signal delays can be used, but the recording head movement is the most common. The removal of normal move out allows much better mixing as well as mixing of several seismic records with proper equipment. Equipment errors must be kept to a minimum in this type work, in order not to produce false reflections. Any process which involves the summation

of a large number of traces is particularly susceptible to recorder speed variation troubles. Systems using direct recording with ac bias are not quite as amplitude sensitive to speed changes, but usually have a higher distortion and slightly less dynamic range.

MONTHLY TESTS

A shake table test of geophones is desirable about once a month; if the geophone groups are extremely large, the time between tests can be increased. One bad geophone in a large group is not nearly as serious as a single bad geophone on a recording channel. A standard geophone and test geophone are used on the shake table. The outputs are compared by applying one geophone output to the vertical plates of an oscilloscope and the output of the other geophone to the horizontal plates of the oscilloscope. The geophones are driven with a steady sine wave drive from the shake table. The oscilloscope pattern should be a line at 45°, if the geophones are matched and the vertical and horizontal sensitivity of oscilloscope are set equal. If the pattern is an ellipse, the geophone outputs are out of phase. If the pattern is a line at low or high angle, the sensitivity or damping of the geophones is different. An uneven ellipse may indicate distortion in one geophone. Abnormal resonances and distortion are much more likely to occur at high amplitudes, so it is desirable to test at very low and very high drive amplitudes.

Another test method which is somewhat less desirable is to stack a number of geophones and use the seismic amplifiers to record the output. The amplifiers should be in the no-automatic gain control position. The output of each geophone should be applied to about three amplifiers with different gain settings. The amplifiers can be divided into three groups, with all amplifiers in each group being calibrated to the same gain position using the test oscillator. All amplifier filters should be in the same wide position. A heavy rock may be rolled down a board or a cap shot to produce a signal. The traces from each geophone should match if the geophones are operating properly.

Another method of comparing geophones is to hang a tray on a long spring and suspend a weight below the tray. The geophones are placed in the tray. The weight is raised and the geophone outputs are observed on a dual beam oscilloscope or by use of calibrated seismic amplifiers as described in the previous test. This test is excellent for showing high amplitude distortion and abnormal resonances.

Cable resistance checks are desirable about once a month and when a crew moves from a dry area to a wet area. Several megohms between pairs and ground is usually quite safe. The actual minimum acceptable resistance depends on impedance of the geophones, the input impedance of the amplifiers, the cable capacitance and inductance. Some cross-feed is tolerable, since it results in a mild mixing of the traces.

In areas where shots are repeatable, the "flip-flop" test is good for reproduci-

ble recording systems. Suppose a normal shot is recorded using filter setting of 15 to 400 cycles per second. This shot is played back at filter setting of 30 to 50 cycles per second. A repeat shot is made and recorded with a filter setting 30 to 50 cycles per second, and played back with filter setting of 15 to 400 cycles per second. The two reproduced records should be nearly identical for proper operation. Difference in the ground roll region of the records may indicate the need for a higher low cut filter setting on recording. Over-modulation may also show up on this test. This test can be useful every time the terrain changes by a marked degree.

The spare magnetic recorder plug-in units as well as the spare seismic amplifiers should be checked once a month.

TESTS EVERY SIX MONTHS

A complete timing test should be made at least every six months. A standard timing fork can be used by recording the output of the standard fork and comparing its output with the timing lines.

Another method is to use a short wave receiver and record a 400-cycle signal from WWV of the Bureau of Standards, Washington, D. C. The timing lines can be compared to the standard 400 cycle signal.

OTHER TESTS

Long range preventive maintenance tests are used by some companies to save time in the field. The tests may be made on a six-month to a year basis. These tests include a complete test of all vacuum tubes on a tube tester. All bias cells are checked or replaced with new ones. Automatic gain control diodes are tested. Amplifier distortion is tested on a distortion analyzer. Modulator and demodulator wave forms are tested on an oscilloscope and necessary calibrations are made. Signal-to-noise ratio tests on the magnetic recorders are made by comparing the output with no input and the output at 100 percent modulation input.

CONCLUSIONS

Improved reliability as well as better seismic records can be achieved by good instrument testing. It is hoped that the present trend of better field tests of seismic instruments will continue, and that the details of the operation of seismic instruments will be open to more people.

DISCUSSIONS AND COMMUNICATIONS

DISCUSSION OF INTERNAL FRICTION OF FINE GRAINED LIMESTONES*

SVEN TREITEL†

I wish to point out an ambiguity in the otherwise excellent paper by Peselnick and Zietz, "Internal Friction of Fine Grained Limestones," that appeared in the April, 1959, issue of GEOPHYSICS. The authors derive a distance attenuation coefficient α_D,

$$\alpha_D = \frac{M''}{2M'C_D}\omega \tag{1}$$

which is proportional to the first power of the circular frequency ω, and show experimentally that α_D is indeed a linear function of ω. The quantity α_D is, however, not the attenuation coefficient usually employed in the pertinent literature.

Consider a plane stress wave propagating in the positive x-direction. The amplitude A_x at a distance x from the source may be written,

$$A_x = A_0 \exp i(\omega t - kx) = A_0 \exp i\omega\left(t - \frac{k}{\omega}x\right) \tag{2}$$

where A_0 = original amplitude at $x=0$, t = time, and k = wave number. In a dissipative medium the wave number k is complex,

$$k = \nu + i\alpha \tag{3}$$

so that (2) becomes in this case,

$$\begin{aligned} A_x &= A_0 \exp i\omega\left(t - \frac{1}{\omega}[\nu + i\alpha]x\right) \\ &= A_0 \exp i\omega\left(t - \frac{\nu}{\omega}x\right) \exp(-\alpha x) \end{aligned} \tag{4}$$

where α is the classical distance attenuation coefficient. Peselnick and Zietz assume a solution to the wave equation of the form,

$$A_x = A_0 \exp i\omega\left(t - \frac{x}{C^*}\right) \tag{5}$$

where C^* is a complex wave velocity, expand $1/C^*$ in a series to first order, and multiply the resulting real and imaginary terms by the ω outside the parentheses of the exponent of (5). As can be seen by direct comparison with (4), their attenuation coefficient α_D is not identical with α.

* Received by the Editor April 29, 1959.

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AUTHORS' REPLY*

ISIDORE ZIETZ† AND LOUIS PESELNICK†

We disagree with Treitel's comment that our attenuation coefficient α_D, is not the same as the attenuation coefficient , α, as used by him.

According to our equation (4) and also his equation (4), the amplitude decay in space is given by

$$A_x = A_0 \exp(-\alpha x).$$

Now, equation (11) as given in our article may be expressed as

$$A_x = A_0 \exp i\omega\left(t - \frac{x}{C_D}\right) \exp\left(\frac{-M''\omega x}{2M'C_D}\right).$$

Treitel's equation (4) is

$$A_x = A_0 \exp i\omega\left(t - \frac{\nu}{\omega}\, x\right) \exp(-\alpha x).$$

Both equations are identical with

$$\alpha = \alpha_D = \frac{M''\omega}{2M'C_D} \quad \text{and} \quad C_D = \frac{\omega}{\nu}.$$

It is immaterial whether one considers the complex velocity, C^* as we do, to represent a decaying wave or the complex wave number, k^* as Treitel does, since the two quantities are reciprocally related by $C^* = \omega/k^*$.

Incidentally, Treitel's complex k is incorrect, for if the absorption term of his equation (4) is to remain as is, then k^* must be given by $\nu - i\alpha$.

USE OF PORTABLE PLAYBACK SYSTEM EFFECTS A SAVING‡

T. O. HALL§

Since developing and operating a portable magnetic playback system which removes electrically the static and dynamic corrections, a considerable saving in preparing corrected record sections has been effected. The field playback machine can handle only a limited number of magnetic tapes.

Table I shows some comparative costs.

The portable playback system has other advantages also, in that the accuracy and speed of field office work is improved. Since the sections are prepared by the same crew that shot the project, the time delay between shooting a line and

* Received by the Editor May 19, 1959.

† United States Department of the Interior, Geological Survey, Washington 25, D.C.

‡ Received by the Editor June 23, 1959.

§ President, General Geophysical Company, Houston, Texas.

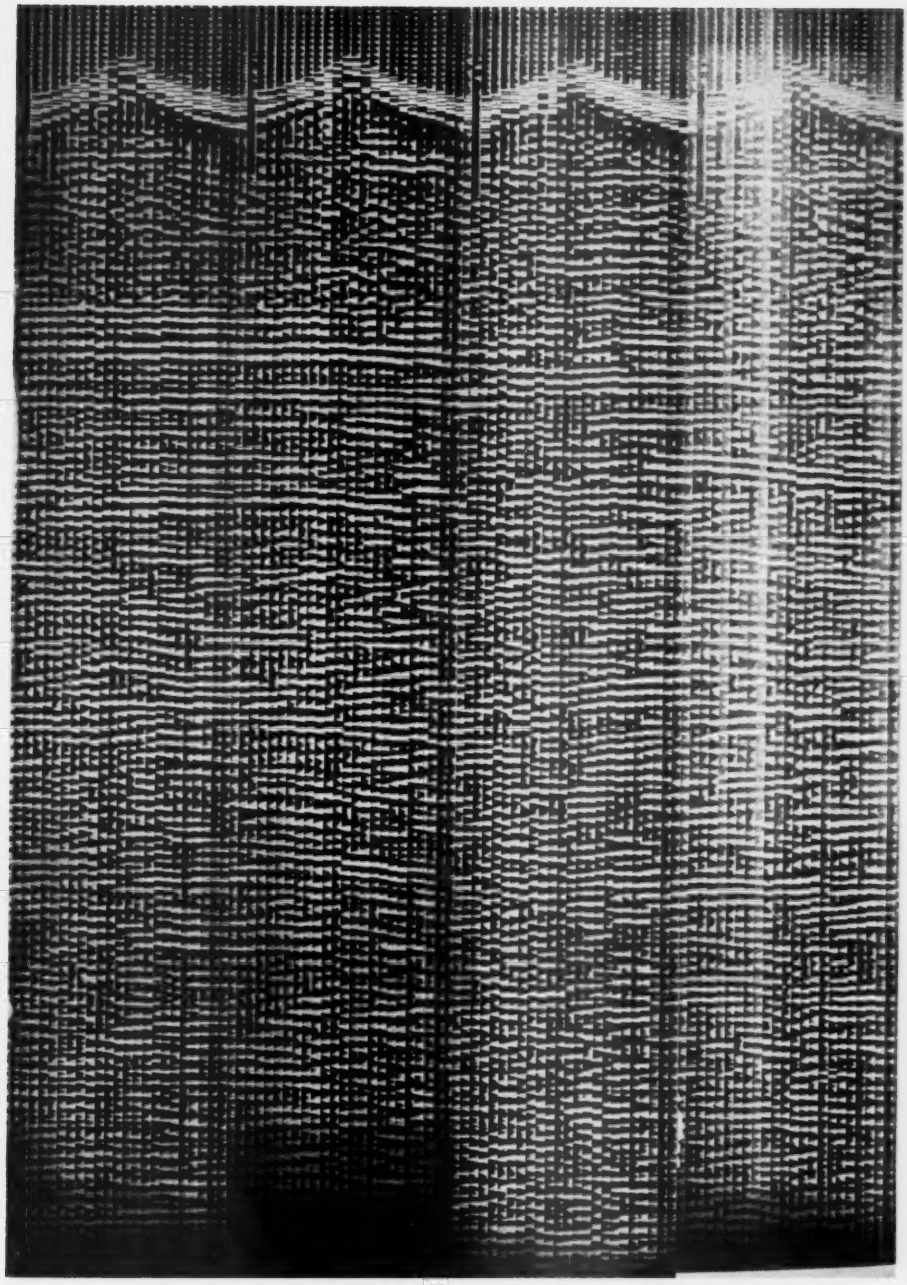

FIG. 1. A variable section made in Canada.

TABLE I

MAGNETIC RECORDING AND PLAYBACK FOR A TYPICAL SEISMIC FIELD PARTY WITH AVERAGE PRODUCTION OF 300 TAPES PER MONTH

	With field recorder and central office playback	With field recorder and playback machine
Tapes and Field Equipment	$1,300.00	$1,800.00
Playback Fees, Transportation and Handling	1,800.00	—0—
Additional Personnel	—0—	500.00 (One man)
Total	3,100.00	2,300.00

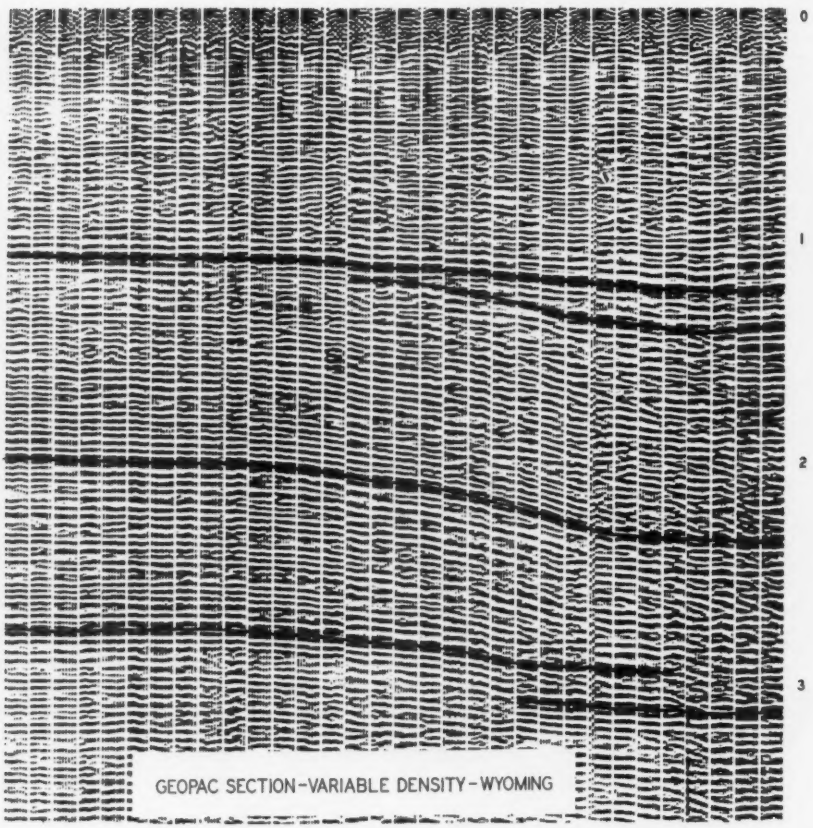

FIG. 2. A variable density section made in Western Wyoming.

completing its analysis is reduced effectively. By the same token, any errors can be rectified much more rapidly.

Conventional "wiggle" record sections can be made with this equipment, and the two record sections shown below show other types of sections which are being made, and which can be made with the portable playback systems.

DEPARTMENTS

PATENTS

O. F. RITZMANN†

ELECTRICAL PROSPECTING

U. S. No. 2,885,633. J. C. Cook. Iss. 5/5/59. App. 4/8/57. Assign. U.S.A.

Electrical Crevasse Detector. A system of detecting the presence of a snow-covered crevasse in glacier ice using a rigid configuration of four flat plate electrodes that are drawn across the snow with two of the electrodes connected to an oscillator of frequency below 400 cps and the other two electrodes connected to an indicator.

U. S. No. 2,887,650. K. A. Ruddock and A. A. Brant. Iss. 5/19/59. App. 5/4/55. Assign. Newmont Mining Corp.

Method of and Apparatus for Geophysical Exploration. An airborne electromagnetic prospecting system using a transmitting coil excited at 390 cps and having receiving coils in zero coupling relationship to the transmitting coil, and measuring the in-phase and out-of-phase components of the voltage induced in the receiving coils at the instant that the exciting current passes through its peak value.

MAGNETIC PROSPECTING

U. S. No. 2,877,407. J. H. Stein. Iss. 3/10/59. App. 11/30/55.

Method and Apparatus for Cancelling Acceleration Noise in a Magnetometer. A system for removing from the indication of a magnetometer the effect of acceleration in a magnetic gradient by combining the output of an accelerometer with the twice differentiated output of the magnetometer.

U. S. No. 2,886,773. M. Potosky, J. H. Davis, and M. Hansberg. Iss. 5/12/59. App. 10/11/54.

Orientation System for Magnetometers. An orienting system for a three-mutually-perpendicular flux-gate type of magnetometer in which the system is nutated at a slow rate and any modulation signal in the detecting element output used to actuate the orienting servomotors to correct misalignment.

GEOCHEMICAL PROSPECTING

U. S. No. 2,876,078. P. J. Moore. Iss. 3/3/59. App. 10/12/54. Assign. National Lead Co.

Well Logging. A method of mud logging in which gas from the mud is first passed over a catalyst that oxidizes hydrogen to water without affecting the hydrocarbon constituents of the gas which is then analyzed for hydrocarbons.

U. S. No. 2,880,142. D. O. Hitzman. Iss. 3/31/59. App. 12/10/56. Assign. Phillips Petroleum Co.

Prospecting for Petroleum Deposits. A microbiological prospecting method in which soil samples are taken and aliquot portions subjected to an aliphatic alcohol as a substrate in a culture medium to permit growth of hydrocarbon-consuming organisms and the colonies developed are counted.

U. S. No. 2,882,014. H. H. Addison. Iss. 4/14/59. App. 5/14/57. Assign. The Texas Co.

Mud Sampling Device. An automatic mud-sampling device having a number of sample containers in a tray that is shifted by a line to the swivel when a predetermined footage has been drilled.

† Gulf Oil Corporation, Patent Department, Pittsburgh, Pennsylvania.

U. S. No. 2,883,856. C. A. Youngman. Iss. 4/28/59. App. 4/14/55. Assign. The Atlantic Refining Co.

Apparatus for Detecting Hydrocarbons in Drilling Mud and Cuttings. A mud logging system in which the mud stream and cuttings returning from the hole are continuously sampled, passed through a grinder together, and delivered to a trap from which gas is analyzed by a hot platinum filament in a bridge circuit whose output is continuously recorded.

RADIOACTIVITY PROSPECTING

U. S. No. 2,876,360. J. A. Victoreen. Iss. 3/3/59. App. 11/16/53.

Apparatus for the Comparison of Sources of Radiation. A radioactivity detector and a calibrated indicating circuit for measuring the activity of a radioactive source.

U. S. No. 2,878,390. F. K. Campbell. Iss. 3/17/59. App. 4/4/55. Assign. ½ to Francis K. Campbell and ½ to The Moran Corp.

Uranium Detecting Devices. A radioactivity detector having an array of Geiger tubes connected in parallel in a lead container with one open end and having coils to which a-c can be applied to screen out all but gamma rays and also having conducting screens to which potentials can be applied to select alpha or beta radiation.

U. S. No. 2,878,391. F. K. Campbell. Iss. 3/17/59. App. 4/4/55. Assign. ½ to Francis K. Campbell and ½ to The Moran Corp.

Uranium Detecting Devices. A detector for radioactive gases having an array of Geiger tubes in a lead case through which the gases are drawn and having grids to which potentials may be applied to select alpha or beta particles.

U. S. No. 2,879,398. A. D. Garrison. Iss. 3/24/59. App. 5/13/53. Assign. Texaco Development Corp.

Detection of Radiation. A scintillation type radiation detector having a radiation transparent cylinder filled with a solution of anthranilic acid in a liquid aromatic hydrocarbon solvent and having windows leading to phototubes at each end of the cylinder.

U. S. No. 2,879,423. R. T. Bayard. Iss. 3/24/59. App. 6/2/54. Assign. Westinghouse Electric Corp.

Counter. A proportional counter for neutrons having a tubular outer electrode and an inner insulated electrode held by sealed thimbles in the ends of the tube.

U. S. No. 2,880,326. L. Musicant. Iss. 3/31/59. App. 10/25/54. Assign. National Radiac, Inc.

Neutron Detector. A neutron detector having a transparent block of a boron ester polymer mixed with a fluorescent substance adjacent to a photocell connected to an amplifier and indicator.

U. S. No. 2,884,529. C. Eggler and C. M. Huddleston. Iss. 4/28/59. App. 4/18/55. Assign. U.S.A.

Gaseous Scintillation Counter. A scintillation counter in which ultraviolet light from excitation emission of a gas such as argon free of quenching contaminants causes visible fluorescence of a solid material and the visible light is detected by a photomultiplier tube.

U. S. No. 2,886,713. R. E. Fearon. Iss. 5/12/59. App. 11/7/55. Assign. Electro Chemical Laboratories Corp.

Geiger Counter Systems. A Geiger counter having an annular cathode and a central wire anode supported on end plates having an opening through which sample gas is introduced, and also having near each end of the anode a guard electrode with a central opening through which the anode wire passes and also allowing passage of the sample gas.

U. S. No. 2,888,571. R. P. Mazzagatti, O. D. Stephens, and A. S. Conners. Iss. 5/26/59. App. 7/6/54. Assign. The Texas Co.

Radioactivity Measuring. A gamma ray detector having a cylindrical cathode and central anode wire and filled with a mixture of helium, argon, and anhydrous ammonia.

SEISMIC PROSPECTING

U. S. No. 2,876,004. R. L. Sink. Iss. 3/3/59. App. 7/12/56. Assign. Consolidated Electrodynamics Corp.

Speed Measurement and Control. A system for controlling the speed of a magnetic tape on playback in which the signal from the timing track is compared with the signal of a standard oscillator by means of counters and the difference count used to control a speed-correcting servomotor.

U. S. No. 2,876,427. W. T. Harris. Iss. 3/3/59. App. 12/30/54. Assign. The Harris Transducer Corp.

Transducer. A hydrophone having a cylindical arc of radially magnetostrictive material fastened to a heavy backing plate to which the ends of the arc are firmly anchored.

U. S. No. 2,876,428. J. D. Skelton and H. B. Ferguson. Iss. 3/3/59. App. 2/7/56. Assign. Jersey Production Research Co.

Seismic Section Printer. A device for correcting field seismograms and having a record drum, a correction drum, and a section drum on the same shaft, each trace being first transferred to the correction drum whose recording head is initially set to an angular position to make the fixed correction and whose playback head is moved during playback by an analog computer to make the variable correction.

U. S. No. 2,876,689. B. B. Strange. Iss. 3/10/59. App. 8/13/57. Assign. Western Geophysical Co. of America.

Apparatus for Making Seismograph Record Sections. A record section printer in which parts of records are printed in sequence on auto-positive reflex paper with a movable mask used to isolate the part to be printed, and having movable clamps for each end of the record with which the operator can adjust and stretch the record so as to make time marks coincide with index marks on the section.

U. S. No. 2,877,554. R. C. Loring. Iss. 3/17/59. App. 10/18/57. Assign. Phillips Petroleum Co.

Seismic Signal Interpretation Apparatus. A geometrical incident wave front plotting device having a number of pivoted and slotted bars arranged to take into account refraction of the incident wave at shallower velocity contrasts.

U. S. No. 2,877,859. W. C. Knudsen. Iss. 3/17/59. App. 8/27/56. Assign. California Research Corp.

Offshore Seismic Prospecting. A device for suppressing bubble noise having a perforated envelope around the shot of a radius about the same as the maximum bubble radius expected.

U. S. No. 2,878,352. L. D. Statham. Iss. 3/17/59. App. 12/14/54. Assign. Statham Instruments, Inc.

Electrical Motion Sensing Means. An accelerometer using a resistance wire strain gage type of transducer to which a paddle in a liquid inertia mass is connected by a spring.

U. S. No. 2,879,860. A. E. Tilley. Iss. 3/31/59. App. 10/11/54. Assign. California Research Corp.

Seismic Prospecting Utilizing Trace Integration. A seismic data processing system in which reproduced geophone signals are recorded with appropriate fixed and variable corrections on a rotating electrostatic recording medium and the integrated charge converted to a composite signal which is rerecorded.

U. S. No. 2,880,404. W. T. Harris. Iss. 3/31/59. App. 5/13/55. Assign. The Harris Transducer Corp.

Compact Resonant Sonar Transducer. A transducer having a tubular magnetostrictive elastic element with a mass fastened to the tube inside each end.

U. S. No. 2,880,510. H. H. Sisson and J. C. Calkins. Iss. 4/7/59. App. 2/3/55. Assign. Robert H. Ray Co.

Apparatus for Locating the Position and Dip of Reflecting Strata and for Plotting Ray Paths. A reflection plotting device having a frame to which flexible rectangular arms are fastened at points representing datum points, the arms being bent to simulate ray paths and having cross bars that represent reflecting horizons.

U. S. No. 2,880,816. M. B. Widess and K. Dyk. Iss. 4/7/59. App. 11/30/55. Assign. Pan American Petroleum Corp.

Seismic Surveying with Shear Waves. A seismic surveying system having a plurality of shear detectors oriented to have transverse horizontal sensitivity axes and using a source made up of a transverse horizontal array of shots that are detonated with time delay between them to initiate a transverse shear wave.

U. S. No. 2,880,966. A. E. Blount. Iss. 4/7/59. App. 1/14/57. Assign. Jersey Production Research Co.

Charge-Planting Motor-Bit Drill. A shot-planting drill for use in water-covered areas having a hose carrying at its lower end a hydraulic turbine that drives a drill bit, and having an annular charge-containing receptacle that follows the drill down and a cable reel that pays out the cap line when the drill stem is retrieved.

U. S. No. 2,880,967. A. E. Blount. Iss. 4/7/59. App. 8/9/57. Assign. Jersey Production Research Co.

Apparatus for Planting Explosive Charges at Submarine Locations. A shot-planting device having a hydraulic turbine-actuated drill with an annular charge-containing receptacle that follows the drill down and has upwardly extending barbs that hold the charge and drill bit in the hole when the drill stem is withdrawn.

U. S. No. 2,882,988. M. B. Dobrin. Iss. 4/21/59. App. 3/16/53. Assign. Socony Mobil Oil Co., Inc.

Elimination of Near Surface Reflecting Effects. A method of eliminating the reflection from the base of the weathered layer by firing a second shot delayed by the travel time of the weathered-layer reflection and of reduced strength in proportion to attenuation of the weathered-layer reflection so that the latter is neutralized, or by combining attenuated records with a corresponding time delay.

U. S. No. 2,883,154. J. P. Daniel, Sr. Iss. 4/21/59. App. 11/30/56.

Method of Positioning Charges and Removing Drill Stems from Shot Holes. A method of loading a shot hole by lowering the charge through the drill stem while the drill is in the hole and forming the detonator wires into a large ball that frictionally engages the inside of the drill stem, and then pulling the drill stem.

U. S. No. 2,883,176. A. Bernstein. Iss. 4/21/59. App. 2/10/58. Assign. Sperry Rand Corp.

Accelerometer. A variable air gap reluctance bridge type accelerometer having an E-shaped core fastened to the case and an armature suspended on flat leaf springs so as to move across the open ends of the core.

U. S. No. 2,884,194. W. T. Evans. Iss. 4/28/59. App. 10/15/53. Assign. Sun Oil Co.

Analog Computer to Determine Seismic Weathering Time Corrections. An electric analog computer in which currents representing times are algebraically added and indicated in a network with adjustable resistances representing velocities.

U. S. No. 2,885,023. H. O. Walker, Jr. Iss. 5/5/59. App. 12/19/57. Assign. The Texas Co.

Reflection Seismic Exploration Method. A method of locating a pinchout by shooting a line over the suspected location and obtaining records showing a reflection from the sloping layer and shooting

the line and obtaining reflections from the immediately overlying horizontal formation at shot-detector distances which give the same angle of ray emergence as the reflections from the sloping layer.

U. S. Re. 24,648. (Original No. 2,810,898). E. P. Meiners, Jr. Iss. 5/12/59. App. 12/28/54, 10/22/57, and 1/12/59. Assign. California Research Corp.

Removing Normal Moveout from Seismic Traces. A device for removing normal moveout during reproduction of a seismogram having the reproducing heads mounted on a deformable beam transverse to the seismogram and gradually deforming the beam during the reproduction.

U. S. No. 2,886,795. R. S. Thatcher. Iss. 5/12/59. App. 5/3/56. Assign. Dresser Industries, Inc.

Apparatus for Generating a Family of Curves from a Single Master Control Element. A device for correcting seismograph traces for normal move-out by means of a carriage with actuators that move slits through which the traces are reproduced.

U. S. No. 2,887,052. D. L. Coursen. Iss. 5/19/59. App. 3/18/58. Assign. E. I. Du Pont de Nemours and Co.

Surface Wave Generator. An explosive assembly for producing a plane wave in the form of a square pyramid of explosive containing spheres of inert material in cubic closest packing and with detonation of the explosive matrix initiated at the apex of the pyramid.

U. S. No. 2,887,053. O. A. Itria and H. L. Tanner III. Iss. 5/19/59. App. 7/30/54. Assign. The Texas Co.

Explosive Assembly. An explosive assembly having male and female connectors for the ends of a column of explosive containers, each connector having a central recess and opening through which a detonating cord can be threaded and tied so as to connect vertically spaced units.

U. S. No. 2,887,054. P. J. Bryan. Iss. 5/19/59. App. 1/13/56. Assign. E. I. Du Pont de Nemours and Co.

Blasting Initiator. An electric delay cap in which the bridge wires are internally shunted by a connector having a resistive fusible material backed by a metal layer for the purpose of reducing arcing upon detonation.

U. S. No. 2,887,577. L. W. Erath. Iss. 5/19/59. App. 2/17/56. Assign. Dresser Industries, Inc.

Means for Attenuating a Signal in Predetermined Patterns. An expander circuit for a seismograph amplifier in which a heated thermistor is substituted for the grounded fixed resistor of a voltage divider and upon reception of first arrivals the heating current is cut off so that subsequent cooling of the thermistor gradually decreases the attenuation.

U. S. No. 2,887,955. A. B. Owen. Iss. 5/26/59. App. 6/29/54. Assign. Texas Instruments Inc.

Seismic Mud Pump. A circulating pump for a shot hole drill having a double-acting reciprocating piston directly connected to a liquid motor driven by a constant displacement liquid pump on the prime mover.

U. S. No. 2,888,089. R. G. Piety. Iss. 5/26/59. App. 9/27/56. Assign. Phillips Petroleum Co.

Seismic Exploration. A reflection seismogram processing system in which adjacent traces each have their positive portion separated from the negative portion, the positive portions of the two traces multiplied, the negative portions of the two traces multiplied, the second product subtracted from the first product, and the result filtered and recorded.

U. S. No. 2,888,256. H. B. Sedgfield. Iss. 5/26/59. App. 4/12/50 and 4/11/51. Assign. The Sperry Gyroscope Co., Ltd.

Accelerometers. An accelerometer in which displacement of the mass is detected by a variable air-gap capacitance in a bridge circuit whose output is fed to coils on the moving system which interact with stationary coils to produce a force that counteracts the acceleration and with current to the moving coils indicated, the stationary coils being energized by current proportional to other factors such as inclination or rate of turn obtained from appropriate indicators.

U. S. No. 2,888,636. L. B. McManis. Iss. 5/26/59. App. 2/26/57. Assign. Dresser Industries, Inc.

Signal Attentuator. An expander for a seismograph amplifier having a thermionic diode bridge with initial attenuation adjustment that is independent of the rate adjustment.

U. S. No. 2,888,663. F. G. Blake and G. A. Schurman. Iss. 5/26/59. App. 3/14/55. Assign. California Research Corp.

Apparatus for Combining Seismic Signals. A seismogram compositing system in which the traces are corrected for normal moveout during playback, recorded on a transfer drum with fixed time corrections, and then combined during second playback and recorded, the drums having independent drives that are synchronized with respect to the timing of the records.

WELL LOGGING

U. S. No. 2,875,612. D. W. Reed. Iss. 3/3/59. App. 12/28/55. Assign. Gulf Research & Development Co.

Subsurface Flowmeter. A thermal type flowmeter in which a current-carrying thermistor is inside a heat-conducting protective tube and the space between the tube and the thermistor filled with an electrically insulating liquid kept in pressure equilibrium with the well fluid.

U. S. No. 2,876,413. D. F. Saurenman and M. P. Lebourg. Iss. 3/3/59. App. 3/30/54. Assign. Schlumberger Well Surveying Corp.

Borehole Apparatus. An arrangement for pressing an electrode pad against the borehole wall, the pad being on two arms forming a parallelogram with the upper arm actuated by a spring-driven plunger.

U. S. No. 2,876,549. B. Adamson and K. L. McNemar. Iss. 3/10/59. App. 1/14/57. Assign. Welex, Inc.

Measuring Wheel. A cable measuring wheel having side sections which clamp expandible shoes forming the periphery of the wheel, the radius of the wheel being adjusted by means of bolts that put pressure on the side sections.

U. S. No. 2,878,886. W. C. Overton, Jr. Iss. 3/24/59. App. 3/12/52. Assign. Socony Mobil Oil Co., Inc.

Acoustic Well Logging with End Shielding. An acoustic logging system using a cylindrical source made up of a series of cylindrical wave transducers placed end to end and separately energized in phase and observing the input to the middle transducer for maintaining constant amplitude of oscillation.

U. S. No. 2,879,126. E. W. James. Iss. 3/24/59. App. 5/10/52. Assign. Sun Oil Co.

Method and Apparatus for Magnetic Recording in a Bore Hole. A system for making a magnetic recording in the sonde of a well logging or surveying apparatus in which the logged parameter is converted to displacement of a magnetic element from a reference element and converted to pulses which are recorded on a magnetic medium.

U. S. No. 2,879,402. M. C. Ferre. Iss. 3/24/59. App. 7/3/53. Assign. Schlumberger Well Surveying Corp.

Directional Neutron Detector. A borehole neutron detector on a pad that is spring pressed against the borehole wall, the detector having a cylinder of boron filled with an ionizable gas and the boron being thin on the side facing the borehole wall and thick over the rest of its periphery so that particles generated by neutrons reach the gas only from the thin portion.

U. S. No. 2,879,403. E. E. Rankin, Jr. Iss. 3/24/59. App. 11/13/56. Assign. Welex, Inc.

System for Radioactive Logging. A gamma-ray logging system in which the integrating time constant of the detector circuit is automatically varied with logging speed.

U. S. No. 2,879,468. J. P. Lamb. Iss. 3/24/59. App. 2/8/54. Assign. Dresser Industries, Inc.

Earth Borehole Investigation System. A guarded electrode electric logging system using a three-conductor cable and in which a-c is supplied to well electrodes and the indications are converted to d-c and fed to the surface.

U. S. No. 2,879,604. P. E. Chaney and R. A. Collier. Iss. 3/31/59. App. 1/17/56. Assign. Sun Oil Co.

Tube Calipering Apparatus. A calipering device having circumferentially spaced feelers with a common actuating member and longitudinally sliding electric contact members between the actuating member and the feelers.

U. S. No. 2,880,389. M. C. Ferre, N. A. Schuster, and F. F. Segesman. Iss. 3/31/59. App. 9/10/54. Assign. Schlumberger Well Surveying Corp.

Electrical Resistivity Well Logging. A logging system in which a main current and an auxiliary current are used to vary the depth of penetration of the resistivity measurement, the auxiliary current being periodically varied to vary the depth of penetration during successive time intervals and with the measured potentials synchronously switched to different indicators.

U. S. No. 2,880,613. B. F. Wiley. Iss. 4/7/59. App. 6/9/55. Assign. Phillips Petroleum Co.

Flow Measuring Apparatus. A well flowmeter having a motor-driven impeller with the motor speed transmitted to the surface as a variable frequency signal, the speed of the motor being adjusted to give no flow in a parallel conduit around a baffle.

U. S. No. 2,881,324. S. A. Scherbatskoy. Iss. 4/7/59. App. 1/4/54.

Radiation Detector. A gamma-ray detector having three scintillation detectors interconnected with anticoincidence circuits and with one of the detectors having a collimating shield so as to obtain indications only for gamma rays in the horizontal plane, and Compton effect and pair formation effects are eliminated.

U. S. No. 2,882,417. F. F. Johnson. Iss. 4/14/59. App. 8/10/53. Assign. Schlumberger Well Surveying Corp.

Well Logging Method and Apparatus. An induced radioactivity logging system in which the sonde has caliper arms mechanically connected to the radioactive source so as to control the distance between the source and the detector in response to variations in borehole diameter.

U. S. No. 2,883,256. P. B. Nichols. Iss. 4/21/59. App. 2/24/55. Assign. The Geolograph Co.

Depth Recorder. A drilling rate and operations recorder having two pens that respectively record the time for drilling each foot of hole and the other drilling operations with a manually operated clutch to selectively couple the pen drives to the operating line.

U. S. No. 2,883,548. P. E. Baker and S. B. Jones. Iss. 4/21/59. App. 11/4/55. Assign. California Research Corp.

Radioactivity Well Log Transmission System. A well signalling system for radioactivity well

logging in which the detector pulses are amplitude discriminated and lengthened so as to use a standard logging cable for transmission to the surface.

U. S. No. 2,883,757. W. J. Oliver. Iss. 4/28/59. App. 12/27/55. Assign. James M. Bird.

Instrument for Measuring the Internal Diameter of Well Bores or the Like. A caliper logging device whose sonde has caliper arms carrying at their outer ends a quantity of radioactive material and having a detector in the body of the sonde.

U. S. No. 2,884,534. R. E. Fearon and J. M. Thayer. Iss. 4/28/59. App. 7/30/49, 4/19/54, and 6/28/55. Assign. Well Surveys, Inc.

Well Logging by Selective Detection of Neutrons. A method of identifying petroleum by neutron well logging in which a source of fast neutrons is used and measuring the loss of neutron flux caused by hydrogen in the formation and the energy loss of neutron flux caused by oxygen in the formation.

U. S. No. 2,884,589. W. M. Campbell. Iss. 4/28/59. App. 5/17/54. Assign. The Atlantic Refining Co.

Well Logging Recording Apparatus. An electric well logging system having a sonde with a large array of electrodes that are automatically switched at each depth location so as to plot the variation of resistivity radially from the borehole for the detection of mud invasion and porous formations.

U. S. No. 2,884,590. W. C. Welz. Iss. 4/28/59. App. 10/16/56. Assign. Schlumberger Well Surveying Corp.

Electrical Well Logging Systems. An electric well logging system having auxiliary focusing electrodes with the auxiliary current adjusted by degenerative feedback to effect substantially zero potential gradient at a point between the electrodes.

U. S. No. 2,885,632. N. A. Schuster. Iss. 5/5/59. App. 8/27/56. Assign. Schlumberger Well Surveying Corp.

Apparatus for Electrical Well Logging. An a-c electric well logging system in which focusing is effected by shifting the phase of the auxiliary current with respect to the main current by means of a degenerative feedback circuit.

U. S. No. 2,886,397. G. J. Butterworth and E. T. Young. Iss. 5/12/59. App. 5/3/48, 9/18/53, and 9/29/53. Assign. Sperry-Sun Well Surveying Co.

Well Surveying Instruments. A pendulum type inclinometer in which the pendulum carries at its lower end a pointed electrode which moves over a concave mosaic formed by the upper ends of a bundle of insulated fine wires with their lower ends against an electrolytic record disc.

U. S. No. 2,887,172. E. V. Hardway, Jr. Iss. 5/19/59. App. 11/30/53. Assign. Robertshaw-Fulton Controls Co.

Well Logging Methods and Apparatus. A permeability logging system having in the sonde a mechanically driven source of volumetric pulsations of frequency such that a quarter wave length is larger than the borehole diameter and two receivers spaced from the source less than a quarter wave length, and comparing the outputs of the receivers to detect differences in acoustical properties of the adjacent formations.

U. S. No. 2,887,298. H. D. Hampton. Iss. 5/19/59. App. 2/26/58.

Well Bore Inclinometer. A well bore inclinometer that is housed in a drill collar and is activated by momentarily interrupting flow of drilling fluid, a pendulum being arranged to uncover a by-pass opening in the drill collar when the hole deviation exceeds a predetermined amount and flow through the by-pass detected by reduced pressure at the surface.

U. S. No. 2,887,777. A. A. Root. Iss. 5/26/59. App. 12/3/56. Assign. American Can Co.

Measuring Device. A device for measuring the cross-sectional area of a tube or bore by means

of a fixed length, variable volume piston having a flexible outer wall and whose interior is filled with fluid connected to a volume indicator.

U. S. No. 2,888,309. D. R. Tanguy. Iss. 5/26/59. App. 10/7/55. Assign. Schlumberger Well Surveying Corp.

Memorizing System. A mechanical device connected to the measuring sheave of a casing perforator that employs casing collar impulses for depth determination and which automatically corrects for the separation between perforator and collar locator.

U. S. No. 2,888,568. S. B. Jones and W. E. Meyerhoff. Iss. 5/26/59. App. 12/2/53. Assign. California Research Corp.

Nuclear Spectroscopy Well Logging. A neutron-gamma method of well logging in which the formations are irradiated by a neutron source shielded to eliminate gamma rays from the source, and neutron capture gamma rays are detected by a scintillation counter that is shielded from thermal neutrons, the output of the counter being fed to a pulse height analyzer which modulates oscillators to convey the information to the surface.

U. S. No. 2,888,569. S. B. Jones. Iss. 5/26/59. App. 1/5/55. Assign. California Research Corp.

Radioactive Bore Hole Logging (Beta Ray Detector). A beta ray detector for use in a well having a phosphor crystal mounted in a window in the wall of the sonde with one or more photomultiplier tubes in contact with the phosphor, the device being particularly suited for detecting radioactive krypton 85 when used as a tracer in a secondary-recovery operation.

(See also Patents 2,876,078; 2,882,014; 2,883,856 listed under Geochemical Prospecting and Patents 2,879,398; 2,879,423; 2,880,326; 2,884,529; 2,886,713; 2,888,571 listed under Radioactivity Prospecting.)

MISCELLANEOUS

U. S. No. 2,876,434. L. M. Oberlin. Iss. 3/3/59. App. 10/1/51. Assign. Phillips Petroleum Co.

Indicating and Control System. A selector circuit for a series of electrically operated gas-lift valves in a well having a dial-operated control and indicator showing the position of the valves.

U. S. No. 2,877,080. J. D. Eisler, C. F. Hadley, and D. Silverman. Iss. 3/10/59. App. 7/2/56. Assign. Pan American Petroleum Corp.

Varaiable-Intensity Recorder. A multichannel recorder having styli in contact with an electrosensitive record, with the styli either rotated across a curved record with electronic switching or with the styli on individual heads that are transversely oscillated and arranged to be shifted longitudinally to introduce time corrections.

U. S. No. 2,878,094. F. C. Dickinson. Iss. 3/17/59. App. 4/9/53 and 4/8/54. Assign. Rotol, Ltd.

Methods and Apparatus for Recording Electrical and Mechanical Vibrations. A high-speed photographic recorder having a rapidly rotating drum with automatic control to record only once on any part of the record which traverses the outside of the drum, and with the record supply and take-up spools mounted on the inside of the drum and automatically adjusting a movable counterweight to keep the drum in balance.

U. S. No. 2,878,578. E. L. Howard. Iss. 3/24/59. App. 10/16/57.

Geophysical Instrument for Measuring the Dip and Strike of Geological Strata. A device for directly measuring dip and strike of an outcrop having a case with a pointer system pivoted on a vertical axis, the system carrying on one side a magnetic compass in a heavy frame in gimbals and on the other side a lighter pendulum-type inclinometer, a divided circle on the case being manually oriented so that its zero is parallel to the compass needle whereupon the strike is read from the pointer indication and the dip is read from the inclinometer.

U. S. No. 2,879,942. H.-G. Doll. Iss. 3/31/59. App. 6/15/53. Assign. Schlumberger Well Surveying Corp.

Tabular Function Generator. A computer for determining the value of a function of two variables in which successive values of the variables are tabulated as indicia in code on two tracks of a moving tape and counted by photocell-actuated counting circuits which develop a control potential that is compared with the function tabulated as a third track on the tape, the counting circuits being controlled by the input variables.

U. S. No. 2,880,413. S. W. Wilcox and W. B. Garrison. Iss. 3/31/59. App. 8/28/53. Assign. Seismograph Service Corp.

Methods and Apparatus for Determining Position. A hyperbolic phase-comparison type of radio location system in which the expansion of the intersecting sets of hyperbolic lines is used to remove ambiguity in the location determination.

U. S. No. 2,881,044. J. D. Eisler, C. F. Hadley, and D. Silverman. Iss. 4/7/59. App. 10/8/56. Assign. Pan American Petroleum Corp.

Electrographic Recorder. A multi-channel recorder in which the respective galvanometer deflections are successively picked up by a series of photocells and converted to high-voltage impulses that are fed to appropriate styli on the edge of a disk rotating transversely to the direction of motion of an electrographic medium.

U. S. No. 2,882,498. G. J. Turre. Iss. 4/14/59. App. 9/20/56. Assign. Hamilton Watch Co.

Galvanometer. A galvanometer for a multielement unit with each galvanometer in a cylindrical mounting with windows opposite the coil and with detachable pole pieces that fit into the windows and are held in place by a thin nonmagnetic sleeve.

U. S. No. 2,883,649. W. H. King, Jr. Iss. 4/21/59. App. 7/26/55. Assign. Esso Research and Engineering Co.

Galvanometer Digitizer. A system for digitalizing a light-beam galvanometer deflection by passing the beam through a screen with opaque bands and collecting the light to a photocell whose output pulses are counted.

U. S. No. 2,884,195. H.-G. Doll. Iss. 4/28/59. App. 9/20/56. Assign. Schlumberger Well Surveying Corp.

Electro-Optical Function Generator. A computer having a pencil of light that passes through a small part of a screen that has zones of different opacity in accordance with the computed function.

U. S. No. 2,884,628. A. L. Loomis. Iss. 4/28/59. App. 7/3/45. Assign. U.S.A.

Long Range Navigation System. A radio location system using two spaced transmitters radiating pulses at regular intervals with the pulses from one transmitter following those of the other transmitter by a known time interval.

U. S. No. 2,886,781. J. R. Tavis. Iss. 5/12/59. App. 12/14/54. Assign. Consolidated Electrodynamics Corp.

Galvanometer Structure. A moving coil mirror-type galvanometer unit for insertion into a multielement assembly and having both galvanometer terminals at the lower end of the unit and an adjusting screw at the upper end of the unit.

U. S. No. 2,886,782. H. I. Chambers and A. W. Fischer. Iss. 5/12/59. App. 5/17/56. Assign. Consolidated Electrodynamics Corp.

Suspension Means for String Galvanometers. A string galvanometer in which the flexible conductor is stretched between the ends of coiled leaf springs.

U. S. No. 2,886,964. J. J. Shapiro and N. M. Winslow. Iss. 5/19/59. App. 1/16/56. Assign. American Instrument Co., Inc.

Porosimeter. A porosimeter having a pressure vessel containing the sample into which mercury is pumped at known pressures and the penetration of the mercury measured.

U. S. No. 2,888,310. E. G. Perry. Iss. 5/26/59. App. 11/2/53. Assign. Texas Instruments Inc.

Recorder. A recorder whose pen is mechanically driven by a driving motor through a pair of biased magnetic clutches whose outputs are connected to the pen arm through a push-pull linkage and with the clutches actuated by the input signal.

SELECTED LIST OF U. S. PATENTS ISSUED DURING MARCH, APRIL, AND MAY OF 1959

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2,875,501	484	2,876,858	12	2,878,467	316
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* A key to the subject classification system will be found in GEOPHYSICS, v. 12, pp. 256–264 (April, 1947).

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Coastal and Submarine Morphology, Andre Guilcher, John Wiley and Sons Inc., New York, 1958, 274 pp., $6.50.

This book will be a valuable addition to the libraries of not only students, but workers in the fields of coastal morphology and marine geology. This is an English translation by B. W. Sparks and R. H. W. Kneese of Guilcher's *Morphologie Litorale et Sous-marine*, first published in French in 1954. The present translation is based on a revised edition of the first publication.

As indicated by the title, the book is devoted to coastal and submarine morphology; however, the major portion of the book (Part I, pp. 15–178) deals with coastal morphology. In Chapter I the physical processes, chemical mechanisms, and biological factors which influence coastal morphology are discussed. Guilcher then points out in Chapter II the difficulty of reconstructing ancient shorelines and reviews current thought on shoreline changes due to eustatic and tectonic movements. The remaining chapters in Part I (Chapters III–IV) are concerned with descriptive coastal morphology, classification, and shoreline evolution.

Submarine morphology is discussed in Part II of this book. As Guilcher points out, the actual significance of submarine morphology is not yet proportional to the large area of the earth's surface covered by water.

The more important concepts and ideas concerning submarine morphology are examined in Chapters VI through VIII. Some will feel the treatment of submarine morphology is not detailed enough. However, our present state of knowledge in this field is such that in only a few years time, much more information will be available and a more complete, world-wide, coverage of submarine morphological features will be possible. Many of the ideas concerning submarine morphology regarded as hypothetical by Guilcher in this edition are rapidly becoming accepted as fact.

One of the outstanding features of this book is the detailed subject biography found at the end

of each chapter. These will be an invaluable aid to those who wish to pursue individual topics further.

Many line drawings are used to illustrate concepts and morphological types. (While the book is not profusely illustrated with photographs, those that are included are excellent.) Large scale regional maps keyed to the local maps illustrating morphological features would be a helpful addition to this book. At present, reference to a geographical atlas is necessary in order to gain a thorough understanding of many of the local morphological features mentioned.

The knowledge embodied in this book is the fruit of many years of intensive study by the author. The geographical coverage of coastal morphological features is such that anyone interested in this field can not afford to be without it.

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Geophysical Surveys in Mining, Hydrological and Engineering Projects, European Association of Exploration Geophysicists, The Hague, 270 pp., $3.25 to EAEG and SEG members, others, $4.50.

The European Association of Exploration Geophysicists are to be commended for this badly needed volume presenting case histories of the use of geophysics in mining, hydrological and engineering projects.

The section on mining consists of 13 papers. Subdividing them geographically, 5 are from Scandinavia and one each from Yugoslavia, Portugal, France, Italy, Holland, the United States and Mauritania. Subdividing them geologically, seven are concerned with sulphide mineralization, two are concerned with uranium mineralization and one each is concerned with iron, coal, native sulphur and ceramic clay.

All the papers describe the application of detail rather than reconnaissance geophysical techniques. The papers from Scandanavia reveal their customary competence in the application of electromagnetic methods. The paper from Yugoslavia describes the discovery of a large low-grade copper pyrite ore body. It should be of great general interest because of the economic importance of "disseminated" deposits. The papers on the use of geophysics on nonmetallics round out a good industry-wide coverage.

Although a geologic description accompanies each article, in some cases a more complete description of the surface conditions would have helped evaluate the geophysical results. By surface conditions is meant such things as quantity and nature of cover, surface indications of mineralization and depth to mineralization.

The volume presents examples of wide interest of the successful application of geophysical techniques in the mining industry. It is an important contribution to the science and art of geophysics.

Geophysical surveys in hydrological projects are discussed in three papers. The first paper analyzes the possibilities and limitations of geoelectric methods as applied in coastal areas of northwest Germany for the establishment of new waterworks or the expansion of old ones.

Examples are given—using resistivity depth measurements—of determining the extent, depth, and thickness of permeable beds in the subsurface which relate to favorable places to drill for water. It is shown also that the extent, depth, and thickness of clay formations can be mapped by electrical measurements.

The second paper presents six case histories of the use of the resistivity method in Illinois for locating water. Since 1935 to date the Illinois Geological Survey has made from 20 to 70 geophysical water investigations per year for water supplies for cities and small towns and individual farms. In the area studied, water comes mainly from beds of sand or gravel in the alluvium of Recent or Pleistocene and pre-Pleistocene streams in upland areas covered by glacial drift. The resistivity work was very helpful in choosing test hole sites for maximum water yield.

The third paper describes how an area of about 108 square miles in Sicily was studied using the resistivity procedure. In six months and from the some 400 "electrical soundings" all the necessary fundamental data concerning underground hydrology was secured. This included a contour map

of the surface of the Blue Clay basement which was used to help locate successful water wells.

This section of the publication demonstrates clearly the wide usefulness of geophysical methods in the search for ground water.

Five papers cover applications of exploration geophysics to hydroelectric projects. In the "great development" of the Rhone valley of France some 12 localities have been investigated geophysically on a stretch of that river about 190 miles long. The importance of geophysical surveys is evidenced by a total of 94 crew months of such work in the last 10 years. Of this effort, 74 crew months were with electrical methods and 20 crew months with seismic methods. Expressed differently the overall program kept one geophysical crew busy for 9.4 months each year.

More specifically, in one survey at the Donzere-Mondragon locality—in the lower Rhone valley—electrical geophysical measurements indicated bedrock at an unexpectedly shallow depth. This finding led to a different layout of the tail race than originally planned and an excellent foundation for the powerplant.

In a second case it was found that soft sandstone—in the subsurface—that could be easily dredged could be distinguished from hard sandstone that must be avoided by a tail race. This was accomplished through seismic refraction measurements.

At the Sault-Brenaz Dam site in the upper Rhone valley a seismic survey supplied data for a contour map on the limestone bedrock on a 3-mile reach of the river. Two buried canyons some 150 ft deep and less than 50 ft wide were discovered and mapped.

In connection with a dam site, search was made for shallow bedrock on the left bank of the Rhine. Resistivity measurements revealed a decrease in depth from 450 ft to 120 ft of a conductive substratum in a study of the configuration of basaltic bedrock. The results were confirmed by a magnetic survey that verified shallow volcanic rock in part of the area studied which was also checked by seismic lines. Results were in good accord with drilling.

A seismic survey of the Lake of Molneno—in the Venetian Alps—showed that the limestone bedrock was over 300 ft deep rather than at shallow depth. The field study concerned water losses from a reservoir. Starting with the reservoir empty, electrical resistivity depth measurements at a series of stations were repeated at each nine meter increase in reservoir level. Results showed that the lower part of the overburden was not glacial clay as had been hoped.

The publication is valuable for geophysicists in the United States and Canada who are so closely tied to finding oil because it shows that the geophysical arts can be successfully applied to other desirable undertakings.

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The Earth and Its Gravity Field, W. A. Heiskanen and F. A. Vening Meinesz, McGraw-Hill Book Company, Inc., New York, 1958, 470 pp., $12.50.

As the title of this book hints, its concern is with what we can learn about the earth's shape and constitution from measurements of gravity on its surface. The book was written by two distinguished geophysicists, whose lives have been spent in research in two fields: first, that of physical geodesy, that is, the part of geodesy which uses gravimetric measurements; and second, in what might be called large scale structural geology. The importance of the book arises from the fact that it makes available a guide to, and a summary of, their work and of work inspired by them. The level of the book is that of graduate work; whatever mathematics is necessary is used without apology.

Chapter 1 is an outline and summary of the material treated in the book while Chapter 2 reviews the data known from seismology and geomagnetism regarding the interior of the earth. Chapters 3–7 deal with the earth's gravity field, specifically the necessary potential theory, the making of gravity measurements and their reduction, and isostasy and its verification through measured gravity

anomalies. Chapters 8 and 9 are devoted to physical geodesy. The final part of the book, Chapters 10–12, deals with problems of tectonophysics, specifically deformations of the earth's crust, development of geosynclines, postglacial readjustment, island-arcs, graben formation, convection currents in the earth, origin of continents and oceans, and polar migration.

Since this review appears in GEOPHYSICS, it seems appropriate to mention those portions of particular interest to exploration geophysicists. Chapter 3 discusses normal gravity formulas and the potential theoretic considerations leading up to them. Chapter 4 is on gravity measuring instruments and to my knowledge is the most complete and up-to-date published account available. Chapter 6 discusses the reduction of gravity measurements, including the free-air, Bouguer, condensation, and inversion reduction methods; terrain corrections; and the expected thorough treatment of isostatic reductions. Isostasy is further considered in Chapters 5 and 7. Chapter 8 discusses reference ellipsoids, geoids, and deflections of the vertical. In connection with the chapters on tectonophysics, two relevant papers published in GEOPHYSICS appear to have been overlooked. They are by C. W. Horton, "Interpretation of isostatic anomalies south of Java, using integral equations and crustal deformation theories," Volume 11, pages 183–194 (1946), and by Ross Gunn, "Quantitative aspects of juxtaposed ocean deeps, mountain chains and volcanic ranges," Volume 12, pages 238–255 (1947).

Section 2–4 contains what appears to be an original presentation of the theory of homogeneous strain, due to Vening Meinesz. It would have been very helpful to readers if the authors had expanded the treatment to make it stand independently or had at least keyed it to some specific well-known textbook. The original Vening Meinesz paper referred to on page 14 is itself somewhat casual in regard to notation and may not be available to most geophysicists. Possibly a desirable uniformity in definition and notation exists among the users of vector and tensor analysis in the Netherlands but this is certainly not the case for their American counterparts.

On page 41 it should have been mentioned what restrictions are placed on the function $f(\theta, \lambda)$, the boundary values of a potential function on the surface of a sphere, so that the series developments listed will be valid.

One usage which causes confusion, at least to those who are not professional geodesists, is the special sense given to the word "spheroid." The customary mathematical definition of spheroid is ellipsoid of revolution; in geodesy it is used to designate a surface differing little from a sphere. Thus it would have been very helpful to explain the exact sense in which the term is used in this book, especially since ellipsoids come up simultaneously. The term "spheroid" occurs first on page 2 and next on page 42, without definitions in both cases. On the latter page the definition of "earth spheroid" is somewhat circular since it is defined in terms of the flattening of the geoid, which flattening is not defined until page 50. My mention of these points is not intended as an adverse criticism; actually the treatment here is a marked clarification of the traditional presentation of this field.

In conclusion, this book provides for those working in geophysics and tectonophysics an authoritative guide to some very fundamental, if abstruse, topics. It is safe to predict that it will become a classic in its field.

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Interpretation of an Aeromagnetic Survey in Indiana, John R. Henderson, Jr., and Isidore Zietz, *U.S.G.S. Professional Paper 316-B*, U. S. Government Printing Office, Washington, 1958, pp. 18–37, 75¢.

In cooperation with the State, the United States Geological Survey made an aeromagnetic survey of Indiana during 1947, 1948, and 1950. Ninety-two county aeromagnetic maps were published during the years 1949, 1950 and 1951, at a scale of 1 inch = 1 mile using a contour interval of 10 gammas. No latitude and longitude corrections were applied to these data.

Professional Paper 316-B shows the results of assembling these data to produce a regional total magnetic intensity map of Indiana at scale 1:500,000 using a contour interval of 50 gammas. This map, together with a regional gravity map prepared by the Indiana Geological Survey in 1953, has been studied by the authors to determine the regional structure of the pre-Cambrian basement

surface. The methods used are those described in the Geological Society of America (1951) Memoir 47, by Vacquier, Steenland, Henderson and Zietz.

In addition to the 1:500,000 aeromagnetic map and the interpreted pre-Cambrian basement surface map, the paper has other regional geological and geophysical maps of interest.

The reviewer regrets that the authors did not make corrections for latitude and longitude while they were revising the regional total intensity magnetic map. Although it could be argued that the lack of such corrections would have little effect upon basement depth determinations, nevertheless a map having corrected data would be desirable when it is to be incorporated into still more widespread displays of magnetic data.

Prof. Paper 316-B is recommended by the reviewer as a good exposition of various reasonable interpretations and speculations concerning geologic structure which can be made using magnetic and gravity data. As such, it is a real contribution to the geophysical literature of Indiana.

ROBERT J. WATSON
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Handbook of Electric Blasting, David M. McFarland and Guy F. Rolland, Atlas Powder Company, Wilmington, 1959, 51 pp., free.

This pocket-sized booklet apparently is intended to acquaint experienced, fuse-cap shooters with the techniques and advantages of using electric blasting caps. Its usefulness to the seismic shooter is, therefore, very limited indeed. It contains a complete explanation of how electric caps are constructed, and the circuitry necessary to detonate them. Much of the latter explanation is not applicable to seismic surveying and, conversely, some information essential to the seismic shooter is not included. Most objectionable to this reviewer is the fact that the greatest dangers to seismic shooters such as shooting near high lines are not even mentioned. Even worse, a casual reading of the section on radio frequency energy could lead a shooter to believe that a few hundred feet is a safe shooting distance from a 50 kw AM broadcast transmitter.

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A Note on the Propagation of a Sound Pulse in a Two Layer Liquid Medium, J. H. Rosenbaum, *Journal of Geophysical Research*, Volume 64, 1959, pp. 95–102.

This paper resolves a discrepancy that exists between theoretical investigations performed by Pekeris (1948) and Officer (1953) and an experimental study pursued by Knudsen (1957), concerning the propagation of a pressure transient in a low velocity liquid layer overlying a homogeneous and isotropic liquid half space. The discrepancy is associated with the amplitude decay of the initial pressure wave with large horizontal distance r. In the theoretical studies, contributions to the initial pressure field arise from both normal mode contributions and an integration around a branch line. Pekeris obtained expansions for these two contributions in which the leading terms decayed as r^{-1}, r^{-2}, r^{-3}, $\cdots$, and r^{-2}, r^{-3}, $\cdots$, respectively. However, the r^{-1} term appears to arrive with a vanishingly small amplitude and hence Pekeris concluded that the first arrival has an r^{-2} dependence. In contrast to this, the investigation of Officer indicated a branch line contribution decaying as r^{-1}. In Knudsen's experimental results, the amplitude of the first pressure arrival actually diminishes as r^{-2}.

Rosenbaum enters into a very detailed theoretical analysis in order to clarify the nature of the initial disturbance in question. He shows that for the first arrival, cancellation occurs between the leading terms of the normal mode and branch line contributions, each of these terms actually decaying with horizontal propagation distance as $r^{-3/2}$. The following terms do not cancel and have an r^{-2} dependence, thus yielding a decay with horizontal range that is compatible with Knudsen's experiments. Rosenbaum's paper illustrates that a meticulous investigation of both the branch line and normal mode contributions is necessary in order to gain an accurate knowledge of the amplitude of the first significant arrivals.

Publication of Rosenbaum's work overlaps with a recent publication of Pekeris and Longman (Journal of the Acoustical Society of America, 1958, *30*, 323) in which the same problem is investigated using a ray theory approach, the relevant computations being performed on a digital computer. Unfortunately, the waveforms published by Pekeris and Longman do not permit an evaluation of the amplitude decay of the first significant arrival at large ranges. It would be of value to derive such information from this exact ray theory technique.

In an appendix, Rosenbaum enters into an interesting discussion of normal modes which are characterized by possessing complex rather than real propagation constants. The imaginary part infers that the disturbance associated with the mode will be attenuated exponentially with horizontal range. Thus in the problem of the low speed water layer, the effect of the complex modes at large ranges will be insignificant in comparison with the disturbance occasioned by the real modes. In the situation involving a high speed stratum, however, real modes do not occur and consideration of the complex modes is of prime importance. The treatment of this problem would be of considerable significance to refraction seismology, and from this standpoint it is noteworthy that Rosenbaum finds it more convenient to treat complex mode contributions by a formulation different from that employed in his current paper. The reviewer would welcome the opportunity to inspect this preferred formulation and expresses the hope that it will be published in the near future.

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Elastiche Wellen in Anisotropen Medien (Elastic Waves in Anisotropic Media), K. Helbig, *Gerlands Beiträge zur Geophysik*, Bd. 67, 1958, pp. 177–211, 256–288.

The propagation of elastic waves in anisotropic media is in this paper considered from various points of view. In an introductory chapter Dr. Helbig discusses phase and group velocity, the three surfaces by which the anisotropy can be characterized, and the adaptation of Fermat's and Huygens' principles to wave propagation in anisotropic media. In the second chapter Hooke's law in its most general form is introduced in the equations of motion, resulting in a set of characteristic equations, which in turn lead to the definition of three characteristic phase velocities of plane waves and corresponding displacement vectors. The phase velocities are found to be functions of the direction of the normal to the plane of equal phase. These well-known generalities are then applied to the special case of transverse isotropy. In chapter three the relationship between a stratified medium and a transversely isotropic one is further explored. Finally, in the fourth chapter a number of model experiments are discussed in which the anisotropic behavior of lamellated materials is examined.

It seems a pity that Dr. Helbig has tried to include so many topics in one article. The result of this has been that, for instance, the discussion of phase and group velocity bogged down in mere formalism, the physical (or geometrical) interpretation of which is not adequately treated. There is no explicit mention of the methods of stationary phase or saddle-point, to which the concept of group velocity is intimately related. The concept of "ray velocity" is introduced without definition. There are other statements which need elaboration like the one on page 185 where it is said that the wave surface separates two parts of space, the inside where the medium is disturbed, the outside where it is not. What is the inside and what is the outside when the wave surface has cusps?

With regard to the dispersion in a stratified medium (page 266), the reviewer would like to call attention to the fact that the phase velocity of waves traveling perpendicularly to the layers does not uniformly approach a limiting value when the frequency is increased. The phase velocity jumps at certain values of the frequency. At these jumps the group velocity is zero.

For those interested in the details of wave surfaces and body wave velocities in anisotropic media, Helbig's article certainly contains many useful results. A list of 57 references contributes to the value of the paper.

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Houston, Texas

PUBLICATIONS RECEIVED

BOOKS

Everyday Meteorology, A. Austin Miller and M. Parry, Philosophical Library, New York, 1959, 270 pp., $7.50.

The Upper Atmosphere, H. S. W. Massey and R. L. F. Boyd, Philosophical Library, New York, 1959, 333 pp., $17.50.

Concise Dictionary of Science, Frank Gaynor, Philosophical Library, New York, 1959, 546 pp., $10.00.

Sounding Rockets, Homer E. Newell, Jr., McGraw-Hill Book Company, Inc., New York, 1959, 334 pp., $12.50.

High Altitude and Satellite Rockets, A Symposium, The Philosophical Library, Inc., New York, 1959, 136 pp., $15.00.

Physiochemical Basis of the Analysis of the Paragenesis of Minerals, D. S. Korzhinskii, Consultants Bureau, Inc., New York, 1959, 142 pp., $7.50.

Man's Journey Through Time, L. S. Palmer, Philosophical Library, New York, 1959, 184 pp., $10.00.

PERIODICALS

American Journal of Science, v. 257, nos. 3, 4, & 6 (March, April & June, 1959)

Annales de Geophysique, v. 15, n. 2 (1959)

Annali di Geofisica, v. 12, n. 1 (Jan.–March, 1959)

Boletin de la Asociacion Mexicana de Geologos Petroleros, v. 11, n. 1 & 2 (January & February, 1959)

Bulletin of the American Association of Petroleum Geologists, v. 43, n. 6 (June, 1959)

Bulletin of Disaster Prevention Research Institute, n. 27 (March, 1959), n. 28 (March, 1959) & n. 29 (March, 1959)

Bulletin of the Earthquake Research Institute, v. 37, pt. 1 (March, 1959)

Chronique de l'UGGI, nos. 19 & 20 (March & April, 1959)

Erdöl und Kohle, v. 12, nos. 4 & 5 (April & May, 1959)

Geologija, v. 4 (1958)

Geophysical Abstracts, v. 176 (January–March, 1959)

Geophysical Digest, v. 6, n. 3 (July, 1958)

Institute of Petroleum Review, v. 13, n. 150 (June, 1959)

Journal of Geophysical Research, v. 64, n. 6 (June, 1959)

Journal of the Institute of Petroleum, v. 45, n. 426 (June, 1959)

Journal of Petroleum Technology, June, 1959

Mining Engineering, v. 11, n. 6 (June, 1959)

ABSTRACTS FROM *GEOPHYSICAL PROSPECTING*

Official Journal of the European Association of Exploration Geophysicists*
Volume VII, Number 1, March, 1959

Ammonium Nitrate: Economy blasting agent for oil exploration

T. O. Hall and J. Martin

This paper has been published in Geophysics, v. 24, 1959, p. 155–163. A record of oral discussion follows its presentation in *Geophysical Prospecting.*

Aspects théoriques et pratiques de la détermination des vitesses d'intervalle en sismique réflexion

J. Y. Chereau and Y. Ledoux

Conventional or continuous velocity logging generally fail to solve the problem of velocities in the whole area of a seismic survey. Surface measurements often bring a large amount of additional information: effect of shallow layers, change of facies, correlations. The authors present a theoretical view on the physical meaning of interval velocities. After a short synthesis of the diverse formulae formerly proposed (Faust, West), the practical manner of using these formulae and the accurate interpretation obtained with the help of geological and geophysical data are shown. Several characteristic examples are finally explained and commented on.

Laboratory determinations of elastic properties of some limestones

J. Kuiper, W. M. L. van Ryen and O. Koefoed

Using a resonance method, determinations have been made of the longitudinal bar velocity and of Poisson's ratio of thirteen different chemically pure limestones. The relation between the velocity and the density showed far less scatter than in the determinations previously published; this is primarily attributed to the high purity of the specimens used. The measurements further showed a tendency of the values of Poisson's ratio to increase with increasing density.

The use of electronic digital computors for the evaluation of gravimetric terrain corrections

M. H. P. Bott

A method is described in which the major part of gravimetric terrain corrections may be estimated by digital computing methods.

Some depth formulae for local magnetic and gravity anomalies

R. A. Smith

Some mathematical inequalities are proved and their relevance to the interpretation of local magnetic and gravity anomalies is discussed. They can be applied to the readings of either a vertical magnetometer or a total field magnetometer or a gravimeter and yield a maximum possible value for the depth below the earth's surface of the top surface of the body producing the anomaly.

The field of a dc element, applied to conductively energized pencilformed ore bodies

K. J. Overholt

The electric and magnetic field of a direct-current element, embedded in a space consisting of two halfspaces differing in conductivity and permeability, is given in a form suitable for integration along a cable. From these formulae is obtained the field when one end of a dc cable is grounded in a highly conducting, pencilformed ore body, considered as a line electrode with uniform current leakage. Numerical examples are given for a horizontal line electrode. The formulae should be useful as a first approximation to the ac case. The validity of this is shortly discussed.

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Impédances et matrices caractéristiques en prospection électromagnétique

J. Loeb

An analogy is established between the propagation of an electromagnetic field in a horizontally stratified conductive medium and that of currents in a linear electric network. This analogy will allow us to know in which case measurements executed at the surface of the ground can provide information about the properties of deeper layers. The situation is the same as when one tries, by means of impedance measurements at the input terminals, to know the properties of electric lines or lumped networks.

A symmetrical linear network establishes between:

Voltages V_1 and V_2 (respectively at input and output terminals)

Currents I_1 and I_2 (respectively at input and output terminals), the relationship

$$V_2 = V_1 \cosh \Gamma - ZI_1 \sinh \Gamma$$

$$I_2 = -\frac{V_1}{Z} \sinh \Gamma + I_1 \cosh \Gamma \qquad (1)$$

Γ is called the "phase constant" and Z the characteristic impedance

The table

$$\begin{vmatrix} \cosh \Gamma & -Z \sinh \Gamma \\ -\frac{1}{Z} \sinh \Gamma & \cosh \Gamma \end{vmatrix}$$

is called "characteristic matrix."

If one then takes the horizontal components of an electromagnetic field, one can compare the voltage V with the horizontal electric field E (in volts m^{-1}) and the current I with the horizontal magnetic field H (in Amp m^{-1}).

For plane waves in vacuum, one gets (Schelkunoff)

$$Z = C \text{ (velocity of light)}$$

A layer whose thickness is D has a phase constant

$$\Gamma = 2\pi D/\lambda \ (\lambda = \text{wavelength})$$

For plane waves in a conductive, non magnetic medium whose conductivity is δ, one gets

$$Z = k\sqrt{j}/4\pi\delta, \ \Gamma = Dk\sqrt{j}$$

where

$$i = \sqrt{-1}, \ \omega = \text{angular frequency}, \ k^2 = 4\pi\delta\omega$$

For the system of waves created by a point-source one expresses the solution, since it is classical, as a sum or integral of different *modes*. For each of these modes, one can still write a bilinear relationship similar to (1), and calculate Z and Γ.

A generalization of this result is given.

Boundary conditions that exist at the surfaces of separation are met by writing the continuity of E and H. This condition exactly corresponds to the fact that there is but one V and one I at the junctions of various sections of lines, or networks.

The characteristic matrix of a cascade of networks—or here that of a horizontally stratified ground—is the product of the matrixes of each network. If, in addition, one knows the end impedance —here the conductivity δ_n of the last layer, supposed to be infinite—one can compute the input impedance R_e of the whole system. In electromagnetic prospecting, it is R_e that conditions the observable field.

Inversely, if measurements were infinitely accurate, the knowledge of the surface field would give all the thicknesses D and conductivities δ of intermediate layers, in the same way that impedance measurements at the input terminals of a cable would allow to locate any failure. The imperfection

of measurements causes the elements located too far away (from the point of view of wave attenuation) to escape detection.

Differential electric log

U. Colombo, G. Salimbeni, G. Sironi and I. Veneziani

A new logging method, which makes use of specific chemical reactions to locate petroleum or other minerals has been developed. The method has been named "Differential Electric Log" (CED).

In this paper the application to the CED method of redox (reduction/oxidation) reactions is discussed. A series of organic oxidants was found, capable of undergoing reaction with crude oil, sulphur, mineral sulphides, lignite. A small amount of an oxidant of this type is added to the drilling fluid and pumped into the borehole where reaction takes place in correspondence with layers containing oxidizable minerals. Two *SP* logs, recorded before and after the oxidation, are compared and the presence of such minerals is thus detected.

A theoretical hypothesis explaining the mechanism of the potential change due to the chemical reaction is proposed both in the case of electronically conducting and non-conducting minerals. The influence of redox potential on *SP* is discussed.

The results of laboratory experiments on several different oxidizable ores and those of field tests performed on pyrite, lignite, and oil wells are reported on and discussed on the basis of the theoretical hypothesis proposed.

On the detection of a spring of mineral water at Bad Peterstal, Schwarzwald, as a result of previous CO_2—measurements in the ground air

E. Budde

In nine small areas in the Black Forest measurements were made of the CO_2 content of ground air, using a method which is based on the difference in heat conductivity between CO_2 on one side and N_2 and O_2 on the other. Measurements during four days yielded four strong CO_2 anomalies. At one of these a well was sunk, which gave a considerable discharge of mineral water.

LETTERS TO THE EDITOR

AID AND COMFORT TO THE EDITOR

Thank you for your letter of April 17. I am glad the Silver Anniversary Issue is in your competent hands. We will try to help make the issue a good one by sending some papers as candidates for the honor of inclusion in the February 1960 issue, keeping in mind your absolute deadline of October 1.

I cannot imagine any improvement on your basic plan for this issue, that is, a portion devoted to historical phases and a portion to unusually good papers.

I hope that the other readers are as well pleased as I am with Dorman's paper in February 1959 GEOPHYSICS, though I suppose that it is inevitable that a few who are not able to appreciate the mathematical work might have registered objections. We have access to a better automatic typewriter now and if we try this means of publication again we will be able to improve the appearance of the offset tables. I greatly appreciate the thought and effort you put into this paper. I consider it an important pioneering step in method of publication important to all geophysicists.

MAURICE EWING
Lamont Geological Observatory
Torrey Cliff
Palisades, New York

Received by the Editor April 23, 1959

GEOPHYSICS NOT PRACTICAL

TO PRESIDENT MCCOLLUM:

Thank you so much for your letter of recent date welcoming me as a new member of the Society. Since I am just one of many tyros in the field I was gratified by your consideration.

I sincerely trust that both the Society and myself will be bettered by my membership acceptance. Indeed, the Society has done much to promote its aims in the past years. While I cannot contribute as yet any paper of scientific value, I do have one suggestion to offer—If you will excuse the possible effrontery of a tyro. Could not the magazine have some fifty percent of its articles written for the beginner and/or the worker in the field of exploration geophysics? Among my friends in the Society, one recently voiced the opinion of many. He said, "Sure, I received the magazine, but I do not have it sent to me here as it is beyond understanding and is no longer practical." He is a man of five years geophysics experience and a college graduate in Geology. While I do receive the magazine here and try to understand some of the articles, I am inclined to agree with him. Most of the articles are far afield from matters concerning the actual exploration geophysics we are doing or expect to do. Could not articles concerning, record computation, normal moveout, formulas for determining weathering data, the preparation of cross-sections, the indication of faults, etc., and the reasons thereof, be included from time to time? While I may not express myself too clearly, I do believe our sister publication from the European Association more nearly fits the bill.

PAUL E. M. IASIGI
United Geophysical Company
Pasadena, California

Received by the Editor May 7, 1959

EDITOR'S REPLY

We can be sympathetic with some of the requests of Mr. Iasigi. As mentioned in the Editor's Report for 1958 (GEOPHYSICS December 1958, p. 897) we earnestly desire to publish more papers useful and understandable to the field man in exploration geophysics. That more papers of this type have not been published is due, almost entirely, to lack of submissions. Articles and short notes on novel computing procedures are welcomed. Papers on fault identification have appeared in GEOPHYSICS, two of them receiving Best Paper Awards.

It is not a function of GEOPHYICS to write articles designed for the beginner. The many good texts on geophysics and the special lessons prepared by virtually all geophysical companies for their per-

sonnel should satisfy that need. The recently released "Lessons in Seismic Computing" and the two volumes of "Geophysical Case Histories" represent SEG efforts to supplement that material.

We take issue with Mr. Iasigi and his friends on the practicality of GEOPHYSICS. It is practical in the important sense of assuring the continuance of exploration geophysics. Just as many present techniques and computing procedures can trace their origin and scientific justification to GEOPHYSICS, so should tomorrow's methods result to some degree from today's technical papers.

We believe that the physics-trained geophysicist, whether a research man or not, can read with some profit most of the papers concerning his special field. The "practical" geophysicist, while awaiting the writing of procedures manuals describing practical application of those papers, might profitably urge the submission of more manuscripts on field procedures.

THE EDITOR

POOR ATTENDANCE AT 1958 AWARDS PRESENTATIONS

Maybe it was the early hour and some of the membership had not recuperated from the parties the night before, or perhaps the registration at the beginning time of the Annual Meeting did not record a sufficient number of the membership in attendance. On the other hand, my impression was that too many were milling around the exhibit booths at this important phase of the Annual Meeting.

In his Letter to the Editor, Pimm states, "In a sense this poorly attended ceremony was a breach of etiquette." This, I believe is a gross understatement of the situation. I sat on the second row from the podium during the presentation of the awards, and it struck me at the time that it was down right rude of those in the lobby and exhibit areas not to be in attendance at this important and propitious part of the Annual Meeting program.

It was not only a dignified insult to those being honored by SEG, but showed a lack of respect for the Society in general, and the program committee in particular.

Every member should read Pimm's comments, GEOPHYSICS, v. 24, April, 1959. p. 270–271.

V. L. JONES
Terrametric Exploration Company
Tulsa, Oklahoma

Received by the Editor June 13, 1959

CONTRIBUTORS

C. H. ACHESON

C. H. ACHESON was born in Johannesburg, South Africa, but has lived in Canada since 1926. Graduating from the University of Toronto in 1937, having majored in Mathematics and Physics, he received an M.A. degree in Geophysics in 1938. He joined the staff of Imperial Oil on graduation and worked in Colombia, South America for the next four and a half years, first as a gravity meter operator and later as party chief and interpreter. Transferring to Western Canada in 1943 he worked with Imperial in Alberta and in the Northwest Territories, in charge of gravity and magnetic work. In 1946 he was transferred to Ecuador, South America as gravity supervisor and interpreter. After a short trip to Peru he was transferred to Colombia where he worked from 1947 to 1950 as senior interpreter in gravity meter and magnetic work. Returning to Calgary in 1950 he transferred to seismic work, and after a few years computing joined the exploration research department. He is at present staff geophysicist in this department. He belongs to the Society of Exploration Geophysicists, American Association of Petroleum Geologists and their Canadian affiliates; and to the American Geophysical Union.

WALTER C. BECKMANN

WALTER C. BECKMANN received a Bachelor of Arts degree in physics from Columbia College in 1949 and has done graduate work in geophysics at Columbia University. In 1949 he joined the geophysics group in the Department of Geology at Columbia University, headed by Dr. Maurice Ewing, now the Lamont Geological Observatory. From 1952 to 1955 he was with the Columbia University Geophysical Field Station in Bermuda, returning to Lamont in 1955.

His work has been focused on underwater sound propagation and on the propagation of acoustic and seismic energies in water-covered areas. He has been Chief Scientist of the Observatory's 202-foot schooner Research Vessel VEMA for portions of cruises VEMA 5, 9 and 12.

He is a member of the Society of Exploration Geophysicists, The Seismological Society of America, The American Geophysical Union and the Royal Astronomical Society.

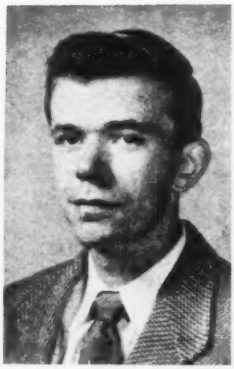
THEODORE R. MADDEN

THEODORE R. MADDEN was born in Boston, Massachusetts in 1925. He entered M.I.T. in 1942, but left to join the U.S. Marine Corps. He served as a radar technician assigned to the 4th Marine Air Wing. In 1949 he graduated from M.I.T. with a B.S. in physics, and entered the graduate school at M.I.T. in the Department of Geology and Geophysics. He was appointed Assistant Professor in Geophysics in July 1958. He has spent most of his summers doing mining geophysical work, except for four summers spent on oceanographic and geophysical cruises of the Lamont Geophysical Observatory.

DONALD J. MARSHALL was born in Marlborough, Massachusetts in 1933. He received his B.S. degree from Massachusetts Institute of Technology in 1954. In June 1955 he received an M.S. degree from the California Institute of Technology with specialization in geophysics. Since that time he has been engaged in further graduate work in geophysics at M.I.T. and is doing thesis work in the field of induced polarization. He was a recipient of a Standard Oil Company of California Fellowship during the school year 1957–1958.

His field experience includes several summers of mining geophysical work.

Upon completion of his graduate work he will join Nuclide Analysis Associates of State College, Pennsylvania.



DONALD J. MARSHALL

W. W. GRANNEMANN was born October 11, 1923 in New Haven, Mo. He received a B.S. degree in Electrical Engineering, and M.A. and Ph.D. degrees in physics from the University of Texas. He was Assistant Professor of Physics at Arkansas Polytechnic College for two years, and worked three years as a research physicist at California Research Corporation.

For the past three years he has been Associate Professor of Electrical Engineering at the University of New Mexico. At present he is Associate Director of the Engineering Experiment Station, University of New Mexico. He is engaged in solid state electronics research at the present time.

W. W. GRANNEMANN

BERNARD LUSKIN

BERNARD LUSKIN graduated in electrical engineering from the City College of New York in 1947 and received a master's degree in E.E. from Columbia University in 1950. He has been on the scientific staff of the Lamont Geological Observatory since 1948, engaged in the design, development and field application of geophysical instruments. Since 1956, he has been a consultant to the Times Facsimile Corporation on geophysical instrumentation. He is a member of the American Geophysical Union, the American Institute of Electrical Engineers, Institute of Radio Engineers, Eta Kappa Nu and Tau Beta Pi.

ARCHIE ROBERTS

ARCHIE ROBERTS received a Masters degree in E.E. from Massachusetts Institute of Technology in 1951 and is a member of Sigma Xi. He has been with the Lamont Geological Observatory since 1953 working both at the Observatory and aboard the Research Vessel VEMA on design and application of geophysical instruments. He was formerly with the Western Electric Company.

Biographies of the following authors appear in earlier issues of GEOPHYSICS as follows: A. F. Gargi, v. 22, p. 945; C. W. Horton, v. 20, p. 710; B. F. Howell, Jr., v. 20, p. 180; Leon Knopoff, v. 22, p. 946; D. T. Liu, v. 24, p. 397; T. C. Richards, v. 23, p. 380; S. H. Ward, v. 18, p. 482.

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LOCAL SECTIONS

Ark-La-Tex Geophysical Society (6), Shreveport, La., chartered March 12, 1949, officers elected in May. *Meetings:* Monthly, last Monday, noon luncheon ($1.50), Captain Shreve Hotel.
Virgil Teufel, *pres.*
J. A. Boydstun, *v-pres.*
R. H. Wardell, *secty-treas.*, Western Geophysical Co., 322 Fairfield Bldg., Shreveport, La.

Canadian Society of Exploration Geophysicists (9), Calgary, Alta., chartered January 24, 1952, officers elected in February. *Meetings:* Monthly, no set schedule.
H. J. Kidder, *pres.*
M. B. Debrin, *v-pres.*
P. J. Savage, *secty-treas.*, Nance Exploration Co., Condon Bldg., Calgary, Alta.

Casper Geophysical Society (11), Casper, Wyoming. Chartered May 23, 1953, officers elected in May. *Meetings:* Monthly, 1st Monday, 7:00 P.M., dinner ($2.75), Townsend Hotel, Casper, Wyoming.
G. L. Ellis, *pres.*
B. A. Tuller, *v-pres.*
Robert Davenport, *secty-treas.*, Wyoming Seismograph Co., Box 631, Casper, Wyoming.

Coastal Bend Geophysical Society (24), Corpus Christi, Texas, chartered May 29, 1959, officers elected in May.
Walter Pfennig, *pres.*
J. W. Bolinger, *v-pres.*
James Vetters, *treas.*
B. C. Johnson, *secty.* Forest Oil Corp., Box 1356, Corpus Christi, Texas.

Cochabamba Geophysical Society (23), Cochabamba, Bolivia, chartered May 4, 1959, officers elected in December.
Paul D. Balbin, *pres.*
Roger Heggblom, *v-pres.*
Frank Ellsworth, *secty-treas.*, Western Geophysical Co., Casilla 1495, Cochabamba, Bolivia.

Dallas Geophysical Society (4), Dallas, Texas, chartered August 7, 1948, officers elected in December. *Meetings:* Monthly, usually 2nd Monday, 8:00 P.M., Fondren Science Bldg., Southern Methodist University.
H. F. Dunlap, *pres.*
E. F. McMullin, *1st v-pres.*
M. S. Hathaway, *2nd v-pres.*
W. B. Heroy, Jr., *secty-treas.*, Geotechnical Corp., Box 28277, Dallas 28, Texas.

Denver Geophysical Society (8), Denver, Colorado, chartered May 19, 1950, officers elected in May. *Meetings:* Monthly, 1st Monday, noon luncheon ($2.35), Petroleum Club.
J. E. Thompson, *pres.*
J. C. Hollister, *v-pres.*
F. L. Travis, *secty-treas.*, Tower Exploration, Inc., 3600 S. Huron St., Englewood, Colorado.

Geophysical Society of Edmonton (23), Edmonton, Alta., Canada, chartered March 20, 1959, officers elected in December.
A. S. Gibson, *pres.*
R. F. Keller, *v-pres.*
R. D. Jacques, *secty-treas.*, Mobil Oil of Canada, Ltd., Financial Bldg., Edmonton, Alta.

Fort Worth Geophysical Society (5), Fort Worth, Texas, chartered August 7, 1948, officers elected in May. *Meetings:* Monthly, 4th Monday, noon luncheon ($1.50), Texas Hotel.
O. A. Strange, *pres.*
P. C. Reed, *v-pres.*
C. H. Thurber, *treas.*
U. A. Rowe, *secty.* Champlin Oil & Refg. Co., Box 9365, Fort Worth, Texas.

Four Corners Geophysical Society (20), Durango, Colo., and Farmington, N. M., chartered June 19, 1958, officers elected in May.
J. P. Badami, *pres.*
F. E. Endacott, Jr., *1st v-pres.*
J. F. Wright, *2nd v-pres.*
G. D. Sindorf, *treas.*
L. E. Schneider, *secty.*, Empire Geophysical, Inc., Box 1484, Durango, Colo.

Geophysical Society of Houston (2), Houston, Texas, chartered February 14, 1948, officers elected in May. *Meetings:* Monthly, noon luncheon.
D. P. Carlton, *pres.*
S. P. Worden, *1st v-pres.*
K. A. Webb, *2nd v-pres.*
S. M. Pena, *treas.*
J. L. Bible, *secty.*, 1045 Esperson Bldg., Houston 2, Texas.

Jackson Geophysical Society (15), Jackson, Miss., chartered May 12, 1955, officers elected in May. *Meetings:* Monthly, during 3rd week, 5:30 P.M., Robert E. Lee Hotel.
R. C. Cole, *pres.*
J. E. MacGregor, *v-pres.*
W. A. McGarry, *secty-treas.*, Pan American Petroleum Corp., Box 689, Jackson, Miss.

Montana Geophysical Society (14), Billings, Mont., chartered April 12, 1954, officers elected in December. *Meetings:* Monthly, 2nd Monday, 7:30 P.M., Billings Petroleum Club.
R. E. Whitmore, *pres.*
W. H. Dawson, *1st v-pres.*
N. L. Hull, *2nd v-pres.*
T. E. Young, *secty-treas.*, Shell Oil Co., Box 2547, Billings, Mont.

New Mexico Geophysical Society (19), Roswell, N. M., chartered September 18, 1957, officers elected in May.
E. J. Medley, *pres.*
R. E. Lawson, *1st v-pres.*
T. E. Daly, *2nd v-pres.*
H. C. Ives, *secty-treas.*, Atlantic Refg. Co., Box 6640, Roswell, N. M.

Geophysical Society of Oklahoma City (10), Okla. City, Okla., chartered September 30, 1952, officers elected in May. *Meetings:* Monthly, 2nd or 3rd Monday.
A. J. Oden, *pres.*
C. L. Howell, *1st v-pres.*
H. J. Fenton, *2nd v-pres.*
W. S. Hart, *treas.*
E. M. Peacock, *secty.*, Sohio Petroleum Co., 1606 N. Broadway, Oklahoma City, Okla.

Pacific Coast Section, SEG (3), Los Angeles and Bakersfield, Calif., chartered April 12, 1948, officers elected in November. *Meetings:* Monthly, 2nd Thursday, noon luncheon ($2.00) Biltmore Hotel, Los Angeles.
R. B. Moran, Jr., *pres.*
W. P. Wilson, *v-pres, N.D.*
J. P. Gates, *v-pres, S.D.*
N. A. Webb, *secty-treas.*, Richfield Oil Corp., 5900 Cherry Ave., Long Beach, Calif.

Permian Basin Geophysical Society (7), Midland, Texas, Chartered January 30, 1950, officers elected in December. *Meetings:* Monthly, 2nd Tuesday, 7:30 P.M., Midland Women's Club.
R. A. Baile, *pres.*
J. E. Clark, *1st v-pres.*
J. W. Rogers, *2nd v-pres.*
R. E. Phipps, *treas.*
D. M. Matson, *secty.*, Midwest Oil Corp., 1500 Wilco Bldg., Midland, Texas.

Regina Geophysical Society (22), Regina, Sask., Canada, Chartered March 20, 1959, officers elected in December.
A. C. Armstrong, *pres.*
D. M. Sawtelle, *v-pres.*
C. E. Dalik, *secty-treas.*, Mobil Oil of Canada, Ltd., 1755 Hamilton St., Regina, Sask., Canada.

Geophysical Society of South Texas (12), San Antonio, Texas, chartered November 9, 1953, officers elected in March. *Meetings:* 1st and 3rd Wednesdays, noon luncheon, Sommers Cafeteria.
W. Harry Mayne, *pres.*
J. W. E. Edmonson, *v-pres.*
P. J. Rudolph, *secty-treas.*, Petty Geophysical Engrg. Co., Drawer 2061, San Antonio 6, Texas.

Southeastern Geophysical Society (13), New Orleans, La., chartered April 1, 1954, officers elected in January. *Meetings:* Monthly, 3rd Monday, noon luncheon ($1.50), St. Charles Hotel.
George Morgan, *pres.*
J. T. McMaster, *1st v-pres.*
D. R. Scheel, *2nd v-pres.*
O. J. Rauschenbach, *secty-treas.*, Continental Oil Co., 414 Carondelet Bldg., New Orleans 12, La.

Southwest Louisiana Geophysical Society (16), Lafayette, La., chartered January 4, 1956, officers elected in December.
Neal Clayton, *pres.*
J. A. Standridge, *1st v-pres.*
C. J. Sieb, *2nd v-pres.*
J. S. Peterson, *treas.*
F. H. Hammons, *secty.*, Pan American Petroleum Corp., Box 1463 OCS, Lafayette, La.

Geophysical Society of Tulsa (1), Tulsa, Oklahoma, chartered February 2, 1948, officers elected in May. *Meetings:* Monthly, 2nd Thursday, 7:00 P.M., meeting only, University of Tulsa, 224 Petroleum Science Hall.
T. S. Green, *pres.*
J. E. Hawkins, *1st v-pres.*
P. H. Garrison, *2nd v-pres.*
R. B. Fisher, *treas.*
B. L. Bass, *secty.*, Texaco, Inc., Box 2420, Tulsa 2, Okla.

Utah Geophysical Society (17), Salt Lake City, Utah, chartered October 29, 1956, officers elected in September.
R. J. Lacy, *pres.*
L. D. Oster, *1st v-pres.*
G. R. Harris, *2nd v-pres.*
J. B. Latimer, *secty-treas.*, Shell Oil Co., 33 Richards St., Salt Lake City Utah.

Asociación Venezolana de Geofísica (21), Caracas, Venezuela, chartered January 5, 1959, officers elected in March.
W. J. Pfeffer, *pres.*
D. F. Warner, *1st v-pres.*
C. W. Penney, *2nd v-pres.*
D. W. Danz, *treas.*
R. L. Garduño, *secty.*, Seismograph Service Corp. of Venezuela, Aptdo 1488, Caracas, Venezuela.

STUDENT SOCIETIES AFFILIATED

Colorado School of Mines Society of Student Geophysicists
Joseph R. Anzman, *secty.* Department of Geophysics, Colorado School of Mines, Golden, Colorado
Meetings: Monthly, 2nd Monday, 4:00 P.M.

Geophysical Society of Saint Louis University
Norman J. Guinzy, *secty.* 410 Vandalia, Collinsville, Illinois
Meetings: Monthly, 2nd Wednesday 7:30 P.M., meeting only, Institute of Technology

SEG Houston Student Section
Reed B. Kubena, *secty.* 1816 Lynnview, Houston 24, Texas
Meetings: to be announced

University of Toronto Geophysical Society
D. W. Strangway, *secty.* 49 St. George Street, Toronto 5, Ontario
Meetings: Bi-weekly, alternate Thursday, 4:00 P.M., 49 St. George Street

University of Tulsa Student Geophysical Society
Fred D. Munzlinger, *secty.* Department of Geophysics, 600 South College, Tulsa, Oklahoma
Meetings: Weekly, Thursday, 4:00 P.M., Petroleum Science Bldg.

Trans-Pecos Student Section
Meetings: to be announced

Pennsylvania State University Geophysical Society
Wm. R. England, *secty.* College of Mineral Industries, University Park, Pa.
Meetings: to be announced

University of Utah Geophysical Society
James D. Morgan, *secty.* College of Mines and Mineral Industries, Salt Lake City 1, Utah
Meetings: Monthly, 1st Thursday Noon, Mines Building. Other special meetings to be announced

A & M College of Texas Student Geophysical Society
Edward C. Hanson III, *secty.* Geology and geophysics dept., A & M College of Texas, College Station, Texas

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Sam Frazier, *President*

MEMBERSHIP APPLICATIONS RECEIVED

Applications for active membership have been received from the following candidates. This publication does not constitute an election but places the names before the membership at large, in accordance with Bylaws, Article III, Section 4. References are listed in parentheses following the names of each candidate. If any member has information bearing on the qualifications of these candidates he should send it to the President within thirty days.

APPLICATIONS FOR ACTIVE MEMBERSHIP

Luigi (NMI) Baulino (C. W. Nicholls, N. P. Cramer & B. B. Strange)
Edwin Ray Browne (A. Thompson, G. B. Matthews, C. B. Scott & G. E. Olson)
Rajendram Seshadri Chellam (D. M. W. te Groen, M. B. Ramachandra Rao & H. Narin)
Lester Knox Funderburk (L. Q. Winter, J. A. Lester, A. W. Musgrave & G. W. Ehlert)
Richard Lewis Gorman (E. S. Driver, L. W. Gardner & F. T. Allen)
Robert Gilbert Hamilton (P. L. Lyons, W. M. Erdahl)
Charles James Linck (W. G. Keck, E. Stahl & R. Ross)
Philip Noel Martin (B. Baum, G. D. Ferrell, A. M. House & R. W. Saubert)
Edward Barrass Nicholls (S. H. Ward, D. J. Salt, J. P. Sheridan & J. B. Prendergast)
Wallace R. Oates
Dewey Elliott Payne (R. Keel, R. Bearnth, H. Wilson & B. Bleker)
Harry Ash Pearce, Jr. (G. M. McGuckire, E. M. Peacock, & H. G. Hadler)
John Geoffrey Drewe Pratt (D. T. Germain-Jones, A. B. Malone, H. D. G. Piggott & V. Fuchs)

APPLICATION FOR TRANSFER TO ACTIVE MEMBERSHIP

Robert H. Bratton (J. S. Page, E. Watts, G. Isensee & R. M. Nugent)
Robert Donald Forester (C. A. Bengtson, S. C. Stonebaum & R. F. Simon)
Francis Cavern French (J. V. Franklin, E. L. DeLoach, C. H. Hightower, O. C. Clifford, Jr.)
John Russell Nock (J. Babb, L. Motiuk, G. Augustat & P. Fatherree, Jr.)
Charles Richard Pelton (F. L. Searcy, R. E. Garten, J. W. Fetrow & H. A. Wakefield)
Calvin Post
George Richard Wulf (C. Kerns, J. W. Peters, F. R. Reeves & J. Hull)

ANNOUNCEMENTS

NEW SEG OFFICERS

The new officers of SEG are as follows: T. O. Hall, President; Frank Searcy, First Vice-President; Dean Walling, Vice-President; Phil P. Gaby, Secretary-Treasurer; and Nelson C. Steenland, Editor. These are for the year 1959–1960, with the exception of the new Editor, who serves until 1961.

The following District Representatives were elected: Bill C. Tucker, Ark-La-Tex Geophysical Society; Norman J. Christie and Dennis R. Mett, Canadian Society of Exploration Geophysicists; Dupree McGrady, Casper Geophysical Society; Charles C. Mason, Coastal Bend Geophysical Society; J. Roger Heggblom, Cochabamba Geophysical Society; William C. Woolley and J. Frank Rollins, Dallas Geophysical Society; Robert C. Kendall, Denver Geophysical Society; G. D. Garland, Geophysical Society of Edmonton; Paul H. Ledyard, Fort Worth Geophysical Society; Brooks S. Stewart and James M. Wilson, Geophysical Society of Houston; Clyde W. Kerns, Montana Geophysical Society; Robert L. Tucker, New Mexico Geophysical Society; Robert H. Peacock, Geophysical Society of Oklahoma City; Forrest F. Lambrecht, Pacific Coast Section; B. F. Owings, Permian Basin Geophysical Society; R. D. Fetherstonhaugh, Regina Geophysical Society; W. Harry Mayne, Geophysical Society of South Texas; Aart de Jong, Southeastern Geophysical Society; Jack D. Wallner, Southwest Louisiana Geophysical Society; William M. Erdahl and James F. Johnson, Geophysical Society of Tulsa; L. D. Oster, Utah Geophysical Society; and Dennis C. Meyer, Asociación Venezolana de Geofísica.

Eugene W. Frowe and E. Glenn Albright were elected Representatives-at-Large.

R. A. Weingartner, Chairman of the Tellers Committee, announced that the following tellers participated in the counting:

Carl Baer	J. G. Jackson	C. D. Roemer
R. W. Mossman	Jack Noble	Marvin Romberg
R. D. Forester	C. S. Moynihan	Robert D. Sprague
John V. Franklin	Donald R. Oksa	Robert J. Watson
T. S. Green	W. E. Pennington	R. A. Weingartner

29TH ANNUAL INTERNATIONAL MEETING

The red carpet is out in Los Angeles to welcome SEG members, their wives and all others who will attend the 29th Annual International meeting there November 9th through 12th. A fine mixture of serious business with the theme of "Integrated Exploration," and social events with special attention to the ladies assures everyone that the time will be spent both profitably and enjoyably.

The post convention tour to Hawaii will add an unforgetable experience for those who go.

Registration for the meeting will start at the Biltmore Hotel at 10 A.M. Sunday November 8 in the galleria and will continue through Wednesday. All events during the meeting will be at the Biltmore.

Sunday from 6 to 8 P.M. a cocktail party will be given for the early arrivals in the Music Room and the Rendezvous Room.

The kick-off luncheon will be in the Biltmore Bowl Monday November 9, followed by a general session from 2 to 5 and a cocktail party from 6 to 8, all in the Bowl.

General sessions, with papers, will continue in the Bowl all day Tuesday and Wednesday, followed by the dinner dance "Hawaiian Holiday" Wednesday evening.

On Thursday all day there will be a general joint session with the Regional AAPG-SEG-SEPM Meeting including presentation of papers, also in the Bowl.

Exhibits will be installed in the Ball Room and Foyer and the Galleria Room and will be open Monday through Friday.

The Research session will be held in the Renaissance Room from 2 to 5 P.M. on Monday November 9 and all day Tuesday.

On Wednesday all day and Thursday morning the Mining session will take place in the Renaissance Room with the Mining luncheon in the same room on Wednesday.

The "Early Bird" breakfast will be held in the Rendezvous Room at 7 A.M. Tuesday November 10.

Thursday from 2 to 5 P.M. the Renaissance room will have a session on Variation of Magnetic and Electrical Fields.

On Thursday November 12 there will be a ladies program in Conference Room 4 from 10 to 11:30 A.M.

A news room for the assistance of the Press will be open from Friday November 6 to the end of the convention.

Convention Headquarters and ladies hospitality facilities will be in the Galleria Room.

The Post Convention Tour to Hawaii will start from Los Angeles International Airport at 9 A.M. on Friday November 13. This provides a unique 9 day planned tour to our colorful new state. Special information on this tour has been mailed direct to all SEG members.

COMPETITION AND AWARD ANNOUNCED FOR BEST ORAL PRESENTATION OF PAPERS

Implementing a resolution of the 1957–58 Executive Committee, the Honors and Awards Committee has worked out plans for an annual competition and award for the best oral presentation of a paper at each National Meeting of the Society of Exploration Geophysicists beginning with the National Meeting in Los Angeles in November 1959.

In launching this program it is felt that not only will a gap be filled in the recognition of outstanding speakers, similar to the recognition by the Best Paper Award of outstanding published papers, but that the attention of our speakers and our audiences will be directed toward more effective and meaningful oral presentation of papers than we have heretofore enjoyed.

Our meetings, both National and Regional (or Local), have always represented one of the chief services the Society offers its members. Much painstaking and time-consuming work is lavished on such meetings by the chairmen and their corps of volunteer workers. The papers presented describe the cream of the up-to-the-minute research, collection of data and organization of results and conclusions in our complex and rapidly advancing art. Presenting a paper and attending a meeting should be a highlight in the experience of every member.

Unfortunately we have all had the experience of suffering with many a speaker through a poorly presented paper which from its title, abstract or even its full content should have been a rich, rewarding experience for both speaker and audience. Some of us, as authors, have suffered even more poignantly as we felt ourselves failing to put over our point after spending months or years on the research and weeks or months on the preparation of our paper.

It is hoped this competition and award will direct the attention of speakers primarily, and audiences secondarily, to the importance of good oral presentations and that the award and the attendant public recognition will provide an incentive to the preparation of papers for the most effective oral presentation.

Moreover, drawing attention to this problem and providing an incentive to speakers is clearly not sufficient. Few authors with a message are natural-born speakers. Even those with a flair for oral presentation and the self-taught who have laboriously attained an acceptable proficiency may benefit from the experiences of other speakers which, over the years have been reduced to easily formulated rules—though diligence and discipline may be necessary to apply these rules.

Accordingly your Executive Committee has launched with this contest a program designed to be helpful to authors preparing to present their papers orally. The first step in this program was the inclusion in the December, 1958 issue of GEOPHYSICS (Vol. XXIV, No. 5) of a paper by Lawrence Y. Faust entitled "The Preparation of a Paper." This paper emphasizes that there is no slip-shod shortcut to the preparation of a paper (and of an author) for good oral presentation. It reaches right to the heart of the problem and is full of practical rules and suggestions. "Speakers in Preparation" are urged to take advantage of this paper and the discussion which follows it, as well as the discussions on pages 636–639 of July, 1959 GEOPHYSICS.

For the time being this award shall be called the "SEG Best Presentation Award" and it is contemplated that a perpetual plaque for public display will be provided upon which the names of the winners will be inscribed annually. Full publicity will be given to the award and its winner as soon as the judging is completed and recognition and a suitable individual "trophy" will be awarded the winner at the subsequent National Meeting.

Your Honors & Awards Committee hopes the Society members respond warmly to this competition and award. Thoughtful suggestions to enhance the value of the program will be welcome.

Curtis H. Johnson
Chairman: SEG Honors
and Awards Committee

SLOTNICK MEMORIAL NOW AVAILABLE

The much awaited text and problem book, "Lessons in Seismic Computing," by M. M. Slotnick, edited by R. A. Geyer, is off the press and now available for distribution. Copies of this memorial publication may be obtained from SEG, Box 1536, Tulsa 1, Oklahoma.

Further details concerning this recent publication by SEG may be found on page 17 in the advertisement section of this issue.

FORMER EDITOR RECEIVES UNIVERSITY PROFESSORSHIP

DR. NORMAN H. RICKER

Dr. Norman H. Ricker has been appointed Professor of Physics at the University of Oklahoma at Norman. He assumed the duties of his new post on September 1.

Dr. Ricker took early retirement from Jersey Production Research Center on January 1, 1959. He has been Senior Research Physicist with the Jersey organization since 1938.

Throughout his career, Dr. Ricker has been an academician at heart, and has long desired to return to an academic atmosphere where he could continue his theoretical research in wave mechanics and his celebrated wavelet theory which has made his name legend among theoretical seismologists.

At his new post, Dr. Ricker will teach one course at the graduate level on wave mechanics, and devote the remainder of his time to theoretical researches in wave phenomena and directing graduate students doing their research projects in this field.

On his retirement from Jersey Production Research Laboratory in Tulsa, Dr. Ricker was presented with the second award of an Honorary Life Membership by the Geophysical Society of Tulsa. He had served this organization as President in 1953–1954, and District Representative 1954–1955.

Prior to his connection with the Jersey organization in 1938, he had served on the research staffs of Western Electric Company (now the Bell Telephone Laboratories in New York), Hughes Tool Company and the Humble Oil and Refining Company, Houston. He organized the geophysical department of the latter company in 1923.

Dr. Ricker has published 14 technical papers, seven of which have appeared in GEOPHYSICS. He is also noted for his invention of the cone type loud speaker while with Western Electric and the plunger lift pump while with Hughes Tool Company.

Dr. Ricker served as Editor of GEOPHYSICS in 1955–1957, and as Associate Editor, 1954–1955. He has served on the Honors and Awards committee for SEG and was the Society's Distinguished Lecturer in 1953–1954.

He received his B.A. with Honors in Physics in 1916, M.A. in 1917, and his Ph.D. in Physics in 1920, all from The Rice Institute. He is a member of American Physical Society, Acoustical Society of America, American Mathematical Society, American Association for the Advancement of Science, American Geophysical Union, Seismological Society of America, Sigma Xi and Society of Exploration Geophysicists.

He is currently a member of one of the technical advisory committees for the Armed Services, and also served with the Office of Scientific Research and Development during World War II.

OKLAHOMA CITY SECTION SPONSORS SYMPOSIA

The Geophysical Society of Oklahoma City sponsored a symposium February 19, 1957, on Seismic Dip Migration and another symposium March 3, 1959, on Continuous Velocity Logging. The material and illustrations presented at these symposia were edited and published in the *Shale Shaker* magazine for September 1957 and May 1959, respectively. The papers presented are listed below by title and author:

SEISMOGRAPH DIP MIGRATION

Shale Shaker for September 1957

The Need for Seismic Dip Migration	W. B. Robinson
Constant Velocity Case	A. J. Oden

The McGuckin Section Plotter	Glenn M. McGuckin
The Application of a Linear Increase of Velocity with Depth to Seismic Dip Migration	J. E. Stones
Chart Migrations	Frank A. Roberts
An Electronic Seismic Dip Plotter	J. A. Westphal
Machine Calculation of Migration Data	E. Usdin
The S. D. P. Dip Plotter	W. S. Hawes
Slide Rule Seismic Computations	R. H. Mansfield
Three-Dimensional Control	G. E. Anderson
Projected Sections for Areas of Steep Dip	Harry J. Fenton
A Comparison of the Various Methods of Dip Migration	Bruce Mayo

CONTINUOUS VELOCITY LOGGING

Shale Shaker for May 1959

Continuous Velocity Logging Method	Howard R. Breck
Presentation of a Velocity Mis-Tie	W. B. Robinson
Areas where Mis-Tie Occurs Between Two-Receiver Velocity Log Data and Check Shot Data	Robert P. Nolting
Possible Causes of Velocity Mis-Ties	R. A. Broding
Limits of Accuracy of Present Sonic Logging Equipment	F. P. Kokesh
Adjustment of Velocity Logs to Tie Geophone Surveys	Warren Hicks

The *Shale Shaker* magazine is a monthly publication sponsored by the Oklahoma City Geological Society, P. O. Box 609, Oklahoma City, Oklahoma.

DIRECTORY OF ENGINEERING SOCIETIES

The Engineering Societies Directory, 1959 edition is now available from Engineers Joint Council. This Directory is the only comprehensive United States listing of engineering and scientific societies, their functional staff personnel and publications.

Societies and organizations are listed in the Directory as well as national and international organizations and all state registration boards for professional licensing. A nearly complete listing of Canadian engineering organizations is also included.

Copies of this publication may be obtained from Engineers Joint Council, 29 West 39th Street, New York 18, New York, at $3.50 per copy.

13TH ANNUAL MIDWESTERN EXPLORATION MEETING

The Ark-La-Tex Geophysical Society, Shreveport, will be host for the 13th Annual Midwestern Exploration Meeting to be held at the Captain Shreve and Washington Youree Hotels in Shreveport April 3–5, 1960. Other midwestern local sections of SEG who will participate include Dallas Geophysical Society, Fort Worth Geophysical Society, Geophysical Society of Oklahoma City, Permian Basin Geophysical Society and Geophysical Society of Tulsa.

General Chairman of the meeting is Mr. S. R. Marsh, The Carter Oil Company, P. O. Drawer 1739, Shreveport, Louisiana. The Program Chairman is Mr. Jackson L. Young, Union Producing Company, P. O. Box 1407, Shreveport, Louisiana. Arrangements Chairman is Mr. S. T. Spradlin, Ohio Oil Company, P. O. Box 1129, Shreveport, Louisiana. Finance Chairman is Mr. Claude N. Valerius, Consultant, 637 Ricou-Brewster Building, Shreveport, Louisiana.

Members who have papers they would like to present at this meeting are asked to submit titles and abstracts to the Program Chairman, Mr. Jackson L. Young.

COASTAL BEND GEOPHYSICAL SOCIETY OFFICERS

The officers of the Coastal Bend Geophysical Society are, from left to right, Walter Pfennig, President; John Bolinger, Vice-President; Billy C. Johnson, Secretary; and James Vetters, Treasurer. The Coastal Bend Section meets on the second Tuesday of each month in the Nueces Hotel, Corpus Christi, Texas.

PERSONAL ITEMS

Three staff changes in exploration and production area organizations have been announced by Shell Oil Company. O. L. ODALE, production manager for Shell's Denver area, has been named production manager for the Pacific Coast area. He succeeds W. F. BATES who has been placed on special assignment on the staff of the vice president for this area. J. W. INKSTER, exploration manager in Tulsa, will move to Houston in the same capacity. He replaces M. S. METZ who will be on special assignment with Shell's head office exploration organization. R. L. TROTT, executive assistant to the vice president, Tulsa area, will assume a similar position in the Houston area.

KALMAN ISAACS, Robert Blesch and Allen Pressman of Aero Service Corporation, Philadelphia, have departed for Paramaribo, Surinam (Dutch Guiana) where they will complete a photogeologic evaluation of the nation. This study is being done in preparation for an extensive airborne geophysical survey of Surinam.

Appointment of JOHN B. FARR as district geophysicist for Pan American Petroleum Corporation's Houston District has been announced by Mr. J. C. JOHNSTON, division exploration superintendent.

The appointment of two vice-presidents and two managers has been announced by R. C. DUNLAP, JR., president of Geophysical Service Inc.

N. W. MANN has been named vice-president in charge of U. S. and Canadian operations, the position held by Dunlap prior to his recent appointment to president. Mann was formerly manager of Western U. S. operations.

G. J. KOHLER, JR., who has been manager of GSI operations in Latin America since September, 1957, has been elected vice-president in charge of that area.

RAY H. WRIGHT, who has been serving as manager of GSI's Canadian operations, will move to Dallas to take over the position vacated by Mann. Wright, in turn, will be succeeded in Canada by Dan F. Brennan.

The election of D. D. MIZE to the Board of Directors of Mandrel Industries, Inc., was announced by George Quist, President, following the annual meeting of stockholders. Mize, a Vice President of the Corporation, is General Manager of Mandrel's Houston operations consisting of the Electro-Technical Labs Division, manufacturers of seismic exploration equipment and the Electric Sorting Machine Division, manufacturers of photoelectric color sorting equipment. Both divisions are located at 5134 Glenmont Drive, Houston, Texas.

Republic Natural Gas Company announces the addition of Mr. A. L. LINEHAN to the geophysical staff.

J. F. FREEL, President of Research Explorations, Inc., 5134 Westheimer, Houston, Texas, has announced the opening of headquarters offices for Research Explorations (Alaska), Inc. in Anchorage. Freel named ERNEST A. PRATT, former Geophysical Sales Manager for Southwestern Industrial Electronics Company, Houston, as General Manager.

M. R. HEWITT, district geophysicist with Pan American Petroleum Corporation, has been transferred from Edmonton, Canada to Midland, Texas, according to Wm. J. Nolte of Fort Worth, North Texas-New Mexico division exploration superintendent. Mr. Hewitt will direct the firm's geophysical program in the southern Permian Basin area. He succeeds J. L. MATAYA, who has moved to Calgary, Canada.

LEO C. FARMER and BYRON W. DICKIE have been elevated to positions of Treasurer and Secretary respectively of National Geophysical Company, Inc., Dallas, it was announced by the firm's president JOHN A. GILLIN.

Formation of a new manufacturing division, Seiscor Manufacturing Company, was announced January 13 by G. H. WESTBY, president of Seismograph Service Corp. Westby said Dr. J. E. HAWKINS, SSC vice president, will assume additional duties as vice president and manager of the new division. Hawkins said that Seiscor Manufacturing Co. has been set up to provide engineering and production facilities and precision equipment to the oil and other industries. "Seiscor will also handle the research, development and manufacturing needs of SSC," Hawkins said.

Formation of the Geophysical Exploration Company, with offices in Houston and Lafayette, La., has been announced by the firm's founders, R. R. MOORE and ROBERT NORMAN. Company headquarters are at 3230 Mercer Street in Houston.

Dr. SYLVAIN J. PIRSON, University of Texas petroleum engineering professor and authority on reservoir engineering, has completed a survey of a newly-discovered French oil field in the Paris Cretaceous basin.

RICHARD A. GEYER has been named manager of the Gravity Department of Geophysical Service Inc., GSI President, R. C. DUNLAP, JR., announced. Since 1954, Dr. Geyer has been chief geophysicist for the Gravity Department, which has its headquarters in Houston, Texas. He succeeds F. E. ROMBERG, who was recently appointed chief geoscientist for the newly-formed GeoSciences and Instrumentation Division of GSI's parent company, Texas Instruments Incorporated.

Contribution of a five-year subscription to GEOPHYSICS to the University of Karachi, Pakistan, has been announced by J. EARLE GRAY, Manager of Foreign Operations, Tidewater Oil Co., Los Angeles.

J. C. SPROULE has been elected President of the Canadian Institute of Mining and Metallurgy.

G. F. KAUFMANN has retired as geophysicist-geologist for Standard-Vacuum Oil Co. His address is now: Dogwood Drive, R.D. 1, Box 312, Yorktown Heights, New York.

DIEGO HENAO-LONDOÑO recently resigned as geophysical supervisor for Petrobras. He is now manager of Pan American Land & Oil Royalty Co., Aptdo. Aereo 12002, Bogota, Colombia.

HERBERT M. DAWSON is no longer associated with Petty Geophysical Engineering Co. His mailing address is Route 13, Box 581, San Antonio, Texas.

MANDREL INDUSTRIES, INC. has entered into an agreement to purchase all of the outstanding common stock of the Well Instrument Developing Company of Houston, Texas, it was announced by George Quist, President of Mandrel Industries, Inc.

WIDCO develops, manufactures and sells well logging equipment and instrumentation. Its facilities and personnel will be integrated with Mandrel's Electro-Technical Labs Division, located in Houston, Texas, under the management of D. D. MIZE, Mandrel Vice President.

CALENDAR OF MEETINGS

1959

November

2– 4 GSA Annual Meeting, Pittsburgh. Pa.

9–12 Society of Exploration Geophysicists, 29th Annual International Meeting, Biltmore Hotel, Los Angeles (Flint H. Agee, General Chairman, United Geophysical Corporation, 1200 South Marengo Avenue, Pasadena 15, California)

12–13 AAPG-SEG-SEPM Pacific Coast Joint Regional Meeting, Biltmore Hotel, Los Angeles.

11–13 Gulf Coast Association of Geological Societies, Houston, Texas.

1960

February

14–18 AIME Annual Meeting, Hotel Statler and Hotel McAlpin, New York City.

April

3– 5 SEG 13th Annual Midwestern Exploration Meeting, Captain Shreve and Washington-Youree Hotels, Shreveport, La. (S. R. Marsh, The Carter Oil Co., Drawer 1739, Shreveport, La.)

25–28 American Association of Petroleum Geologists—Society of Economic Paleontologists and Mineralogists, Annual Meeting, Atlantic City, New Jersey

October

2– 5 Society of Petroleum Engineers of AIME, Fall Meeting, Denver, Colorado.

19–21 Gulf Coast Association of Geological Societies, Biloxi, Mississippi.

November

7–10 Society of Exploration Geophysicists, 30th Annual International Meeting, Moody Convention Center, Galveston (Walter B. Lee, Jr., General Chairman, Gulf Oil Corporation, Drawer 2100, Houston 1, Texas)

1961

November

5– 9 Society of Exploration Geophysicists, 31st Annual International Meeting, Denver (Ralph C. Holmer, General Chairman, Bear Creek Mining Co., 516, Acoma, Denver 4, Colorado)

10–12 GSA Annual Meeting, Denver, Colorado.

1962

September

17–20 Society of Exploration Geophysicists, 32nd Annual International Meeting, Calgary, Alberta

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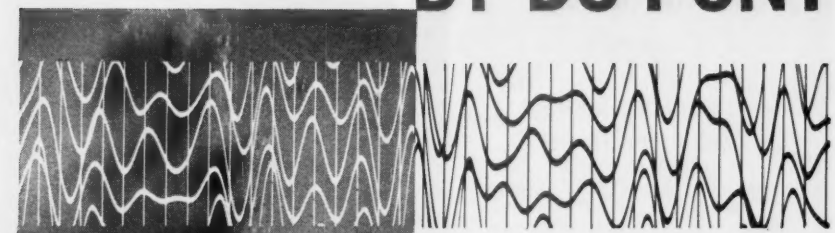

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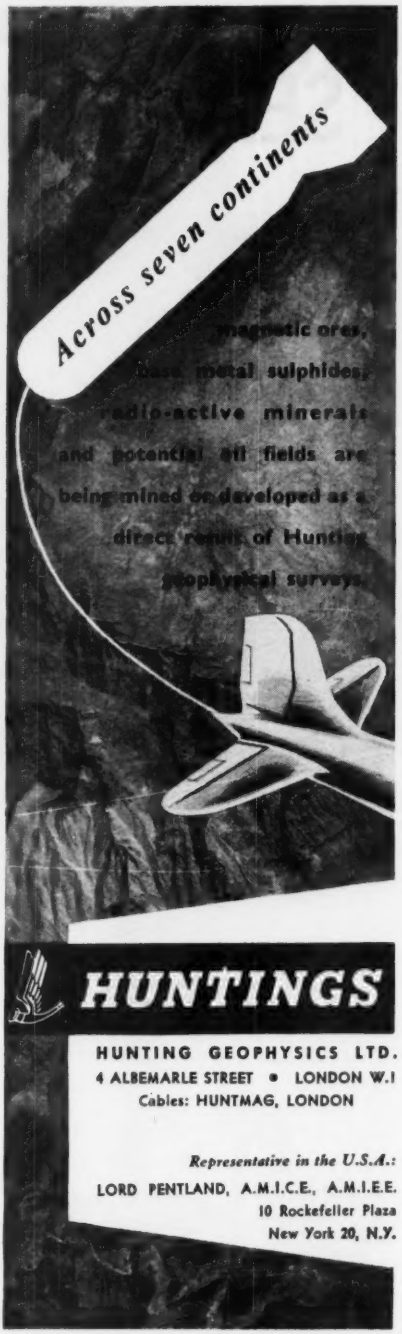

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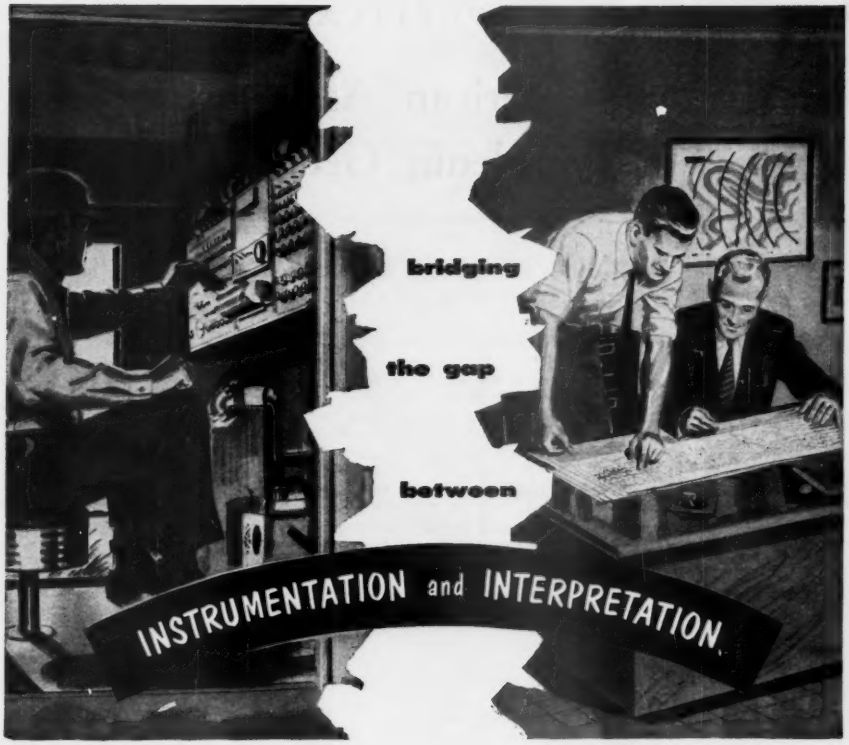

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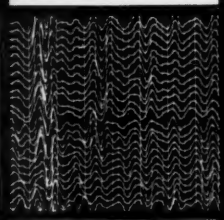

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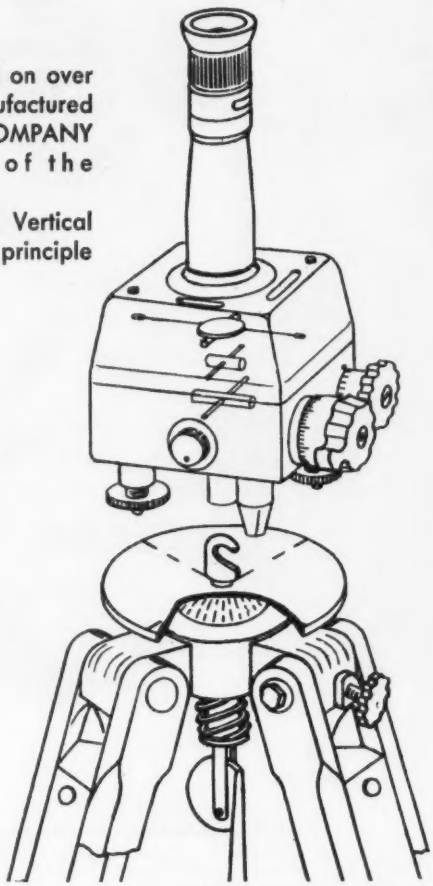

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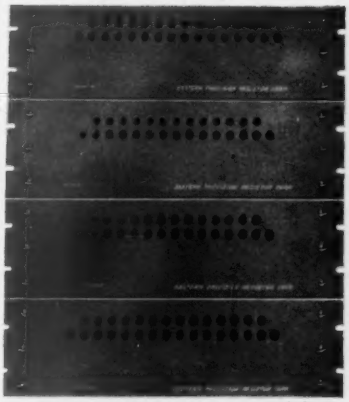

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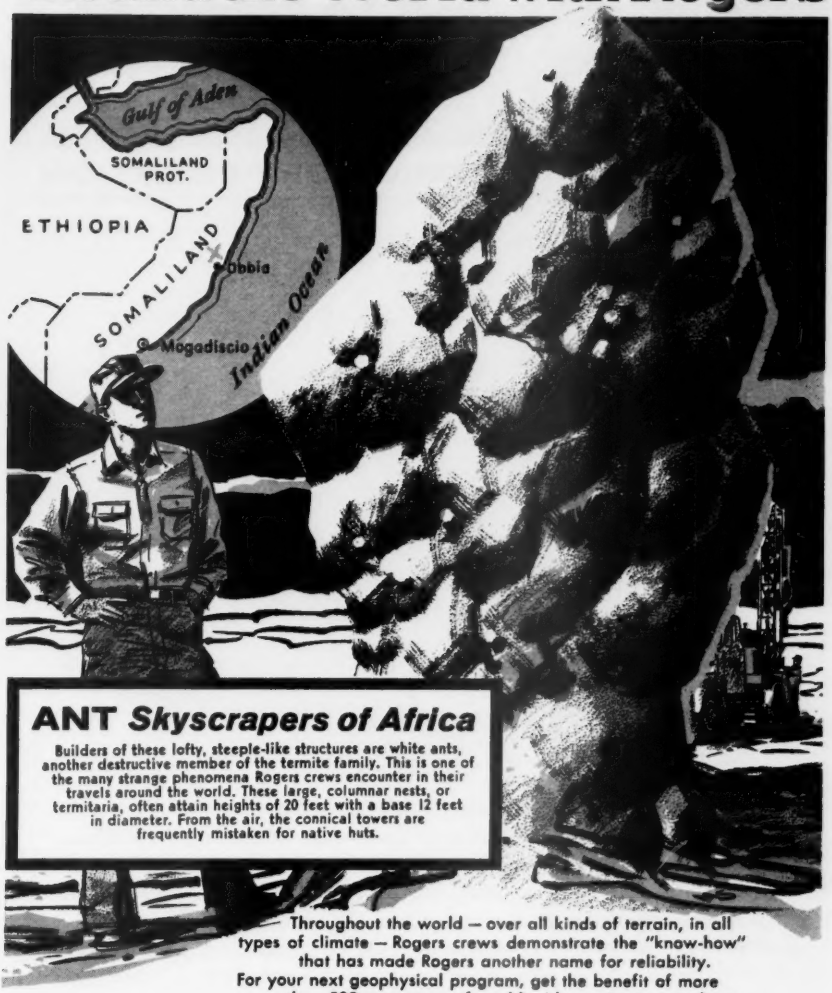

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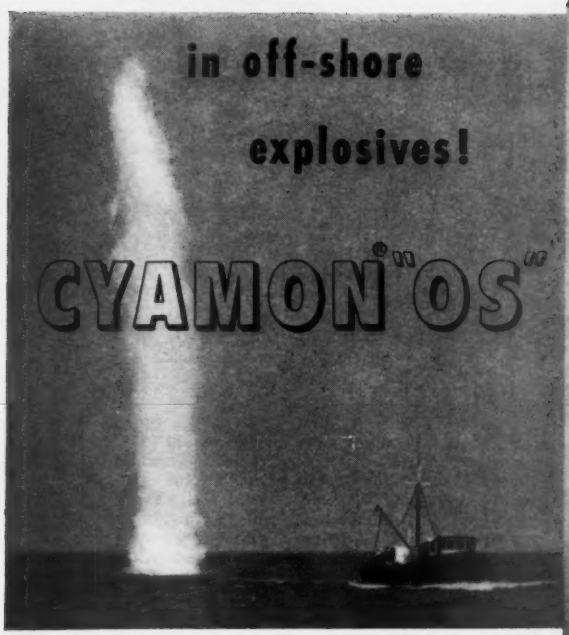

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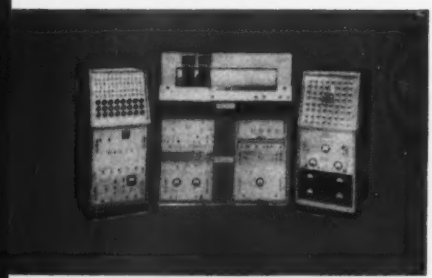

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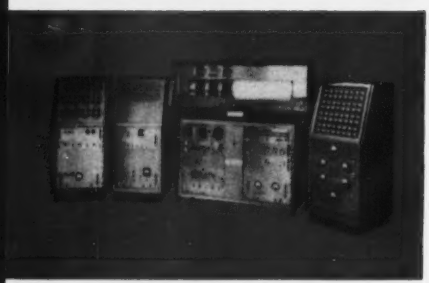

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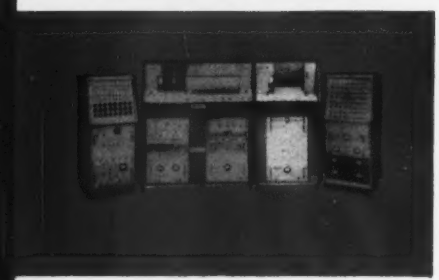

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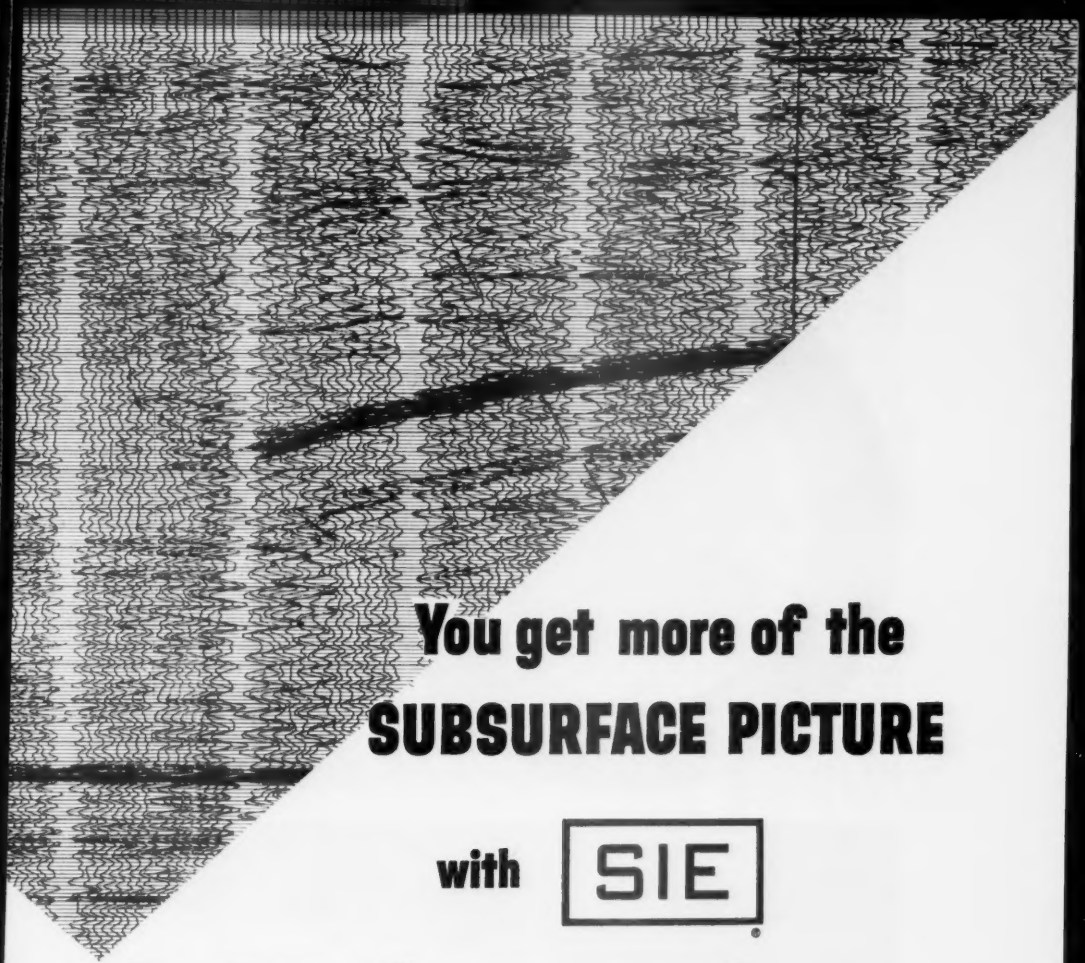

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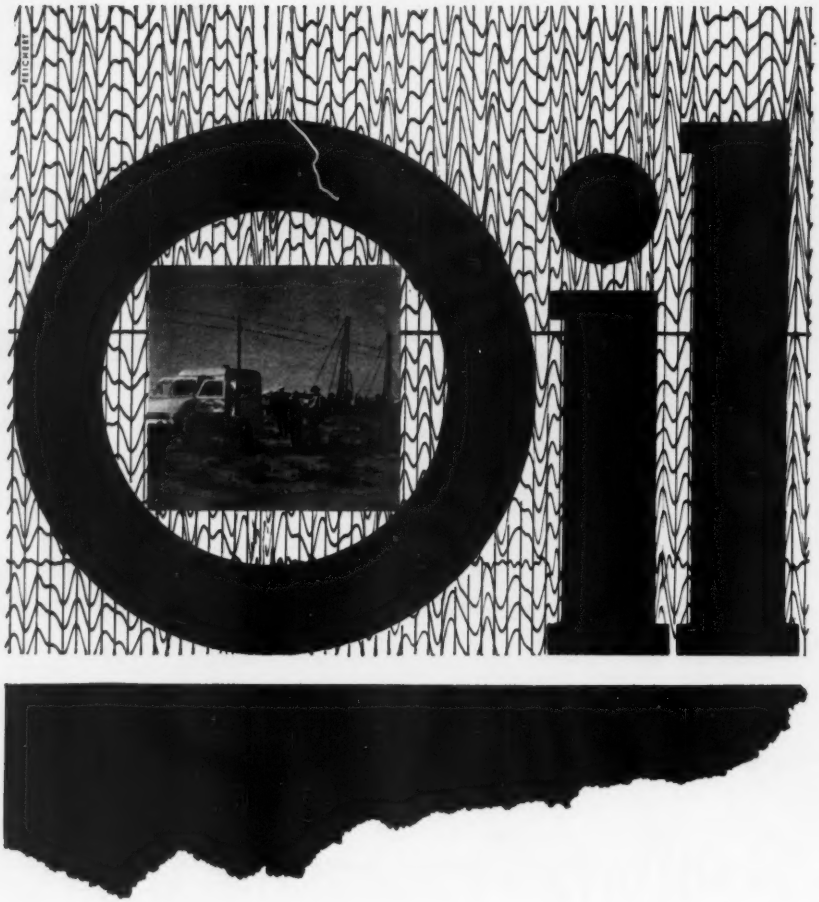

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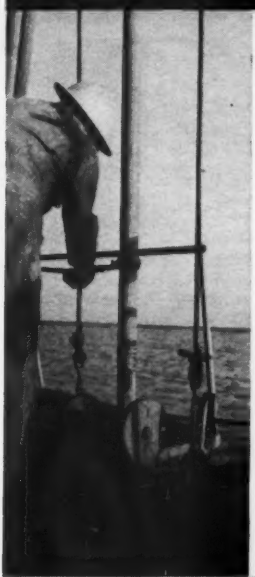
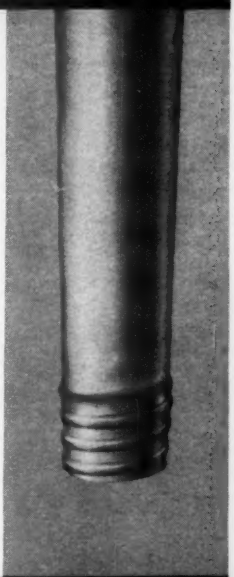


Field tests prove Tex-Tube Shot-Hole Casing best! Fast, strong, easy-to-handle. Two turns completely engage speed coupler. Tapered ends mean easy stabbing. Strong rolled threads assure good recovery. 16 gage weighs only 20 lbs. per length. 19 gage weighs only 13 lbs. per length. For export, ten lengths to a package, four packages to a 4-Pack. Unband only what you need. Available from stock at the stores listed below.



BAKERSFIELD Par-Tain Exploration Co. **BATON ROUGE** Tex-Tube, Inc. **BEEVILLE** (Tex.) H&T Sales Co. **DALLAS** Engineering Supply Co. **HOUMA** Tex-Tube, Inc. and Bilderback Dynamite Co. **HOUSTON** Tex-Tube, Inc. **LAFAYETTE** Bilderback Dynamite Co. **MILLS** (Wyo.) Teton Tool Co. **OKLAHOMA CITY** Deupree Distributing Co. and Grove Hardware Co. FOREIGN: **CALGARY** Seismic Service Supply, Ltd. **CARACAS** Venezuelan Supply, C.A. EXPORT: **NEW YORK CITY** National Supply Co., Export Division.

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A COMPLETELY UNITIZED
HIGH FIDELITY FM
MAGNETIC RECORDING
SEISMOGRAPH SYSTEM

An economical one-package unit for magnetic recording and monitoring, the MS-15 incorporates all of the high-fidelity advantages of the frequency-modulation method plus linear phase shift seismic amplifiers to insure accurate recording of seismic data . . . all of this at the same cost as AM equipment.

Playback of tapes is made sequentially through a high quality seismic amplifier and electrically recorded to eliminate darkroom and developing facilities and minimize complexity and cost.

FM high-fidelity magnetic recording, proven field dependability, ease of maintenance, operating convenience and flexibility, unmatched compactness . . . the MS-15 combines every feature required for successful exploration.

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MINIATURIZED RAYDIST DM SYSTEM

SAVES OIL COMPANY THOUSANDS OF DOLLARS

HYDROGRAPHIC AND GEOPHYSICAL SURVEY ALONG 75 MILES OF COASTLINE COMPLETED WITHIN 40 WORKING DAYS

The Pacific Petroleum Company, an affiliate of Richfield Oil, selected the new, miniaturized Raydist Type DM system for use in a geological survey off the coast of Peru.

According to the Chief Geophysicist for the survey, the selection of Raydist over other position determining systems resulted in an over-all savings of thousands of dollars.

Since time was limited, the equipment was shipped by air from Hampton, Virginia, to Peru, South America. Raydist, weighing only one-tenth of competitive systems, saved $4,000 in shipping costs alone. Within twenty-four hours after clearing customs, Raydist was on the job.

The new, miniaturized Raydist system saved many days of installation time since the small, light, battery-operated shore stations can be set up within thirty minutes.

Raydist, maintained by only two operators, saved additional transportation costs and also reduced the logistics problem especially important in this remote area.

Raydist provided a continuous permanent record of the vessel's position with relation to two selected shore sites which enabled the survey boat to return to any point at a later date with extreme accuracy.

Raydist left Hampton, Virginia, on December 10 and returned home February 2 after having completed a hydrographic survey along a 75 mile coastline in Peru, South America.

An observer from another oil company, after seeing Raydist in operation, said, "I was favorably impressed by the portability and compactness of the system. I was also favorably impressed by the apparent accuracy and repeatability of the system. The whole set-up appeared efficient, and I feel sure it would be of value in our operation."

In case after case, Raydist has proved itself a superior tool for all hydrographic operations. We welcome your inquiries.

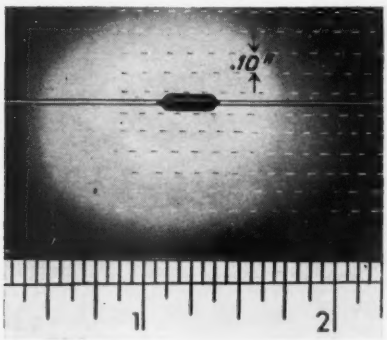
HASTINGS-RAYDIST, INCORPORATED

TEL: PARK 3-6531 HAMPTON, VIRGINIA

(Continued from page 10)

SUBMINIATURE CERAMIC CAPACITORS

MUCON CORPORATION, 9 St. Francis St., Newark, N.J., announces a new series of subminiature ceramic capacitors called "NARROW-CAPS", designed to be no more than .095″ wide to fit within 1/10″ modular spacing.



Capacitance values available in "NARROW-CAPS" are 100 mmf; 250 mmf; 500 mmf; 750 mmf; and 1,000 mmf. Tolerance is ±20%. Body length of the first four sizes is .250″ max., and the length of the 1,000 mmf. unit is .300″ max.

Temperature range is —60°C. to +125°C. Power factor is less than 2.5%. The no. 26 tin copper gauge leads are 1½″ long min.

"NARROW-CAPS" are ideal for the smaller unit concept of 1/10″ modular spacing in printed circuitry.

"SANDWICH" TAPE

Oxide rub-off on recording heads—one of the biggest headaches in data processing—has virtually disappeared at computer installations that have switched to "sandwich construction" magnetic tape, says its manufacturer.

Minnesota Mutual Life Insurance Company has detected no wear on sandwich tape since substituting it for all conventional tape in their Burroughs 205 computer nine months ago.

"The only time we've had to change tape is when there has been mechanical damage to the tape," reports Herbert Cherry, director of data processing.

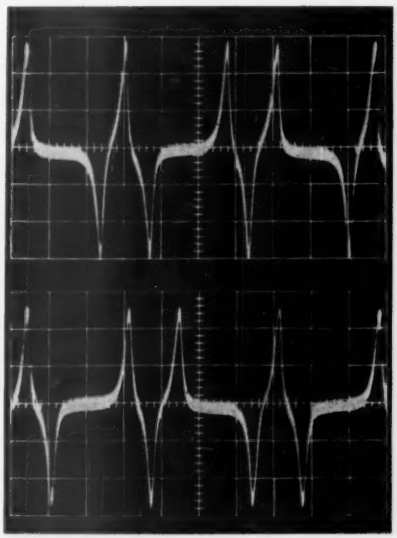
The secret behind sandwich tape's success lies in its protective "armor"—a 50 micro-inch plastic layer which shields its iron oxide coating from direct contact with recording heads. The tape presents to the recording head a smooth non-abrasive surface rather than the exposed particles.

Conventional tape coating gradually wears off during the rigorous workouts imposed upon it by computers. Powdered oxide collects on recording heads, as well as on the surface of the tape itself—either condition results in signal dropouts.

This oxide rub-off problem was what prompted Minnesota Mutual's switch to sandwich tape.

The company points out that tape in their Datafiles had been "picking up" or "dropping" bits, due to oxide rub-off on the recording heads. This in turn would make the capstans slippery and the tape would slip "out of step" during the rapid stop/start operations, causing wrong information to be transmitted.

"By replacing the entire Datafile bin with 'Scotch' sandwich tape No. 188 we eliminated 90% of our tape-read troubles," points out Jack Gerver, senior maintenance engineer in charge of the company's computer room. Sandwich tape is made by **Minnesota Mining and Manufacturing Company, 900 Bush Ave., St. Paul 6, Minn.**



(Continued on page 64)

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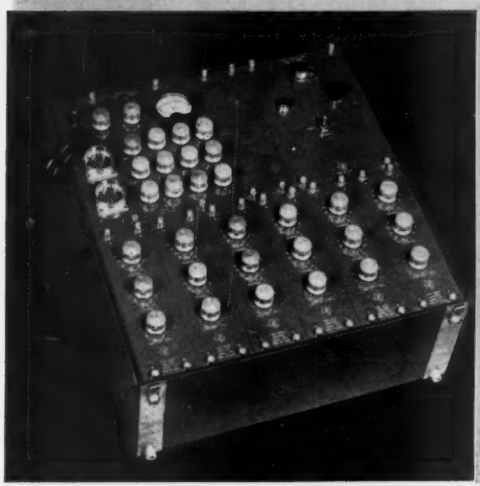
TI **VLF VERY LOW FREQUENCY SEISMOGRAPH** AND **S-36 HIGH-OUTPUT 2-CYCLE SEISMOMETER**



Although the Refraction Seismograph was used as an exploration tool many years before the Reflection method, it was virtually abandoned during the thirties because of the inability of existing equipment to record low frequencies and build up a satisfactory signal-to-noise ratio.

SAVE UP TO 50% ON DYNAMITE— SHOOT ANY TIME OF THE DAY!

Now, the thoroughly field-proved *VLF* Refraction System provides highly usable results for large area surveys or in areas unworkable by the reflection method. Excellent first breaks and second arrivals have been recorded while using less than half the dynamite required by other systems. Furthermore, the *VLF's* high signal-to-noise ratio permits shooting during the usually windy mid-day hours when other systems cannot produce usable results. With frequency response down to one cycle on the amplifiers and to two cycles on the S-36 seismometers, the versatile *VLF* system is equally satisfactory for the most difficult petroleum exploration programs, mining surveys, and civil engineering projects.

You can be sure of the best attainable refraction results with the compact and portable 12-channel *VLF* system. Write for complete information — specify Bulletin S-308.

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Seismafon system

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McCollum Ray International, Incorporated is ready to serve your foreign seismic needs with GEOGRAPH, the newest exploration technique. A world-wide organization, McCollum Ray combines the weight dropping method with experience gained from geophysical operations in more than 30 foreign areas.

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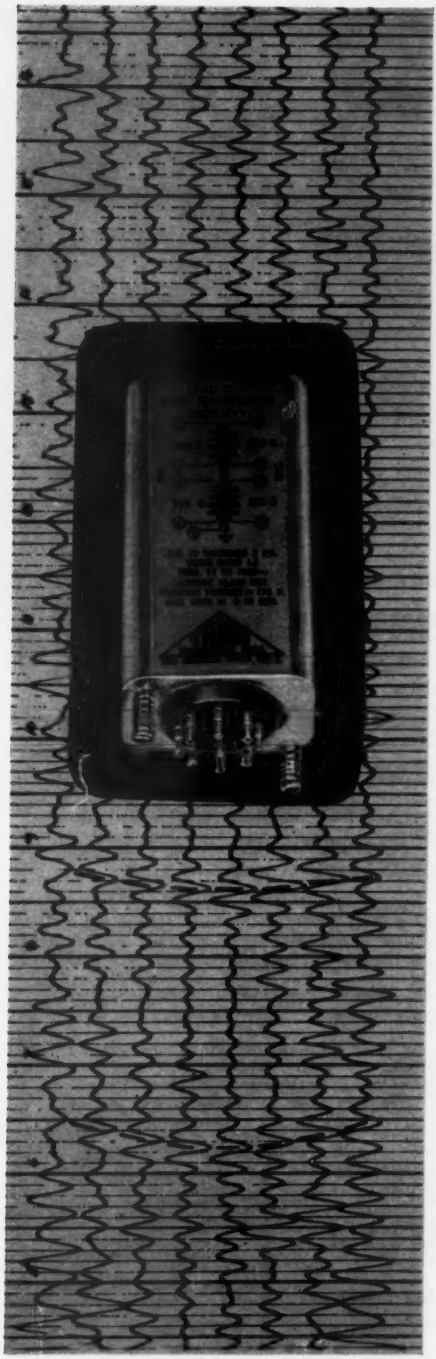

before...
during...
and after

Here are three excellent reasons why designers of precision geophysical instruments specify Triad transformers:
1. Every coil on every Triad geophysical transformer is tested before impregnation.
2. Tested again during assembly.
3. Tested again after completion. Result: accuracy, reliability, and uniformity.

In addition to the Triad geophysical transformers listed in our catalog (all especially designed to meet the unique and difficult conditions of geophysical prospecting) we will supply units tailored to your specifications — at reasonable cost and in reasonable time.

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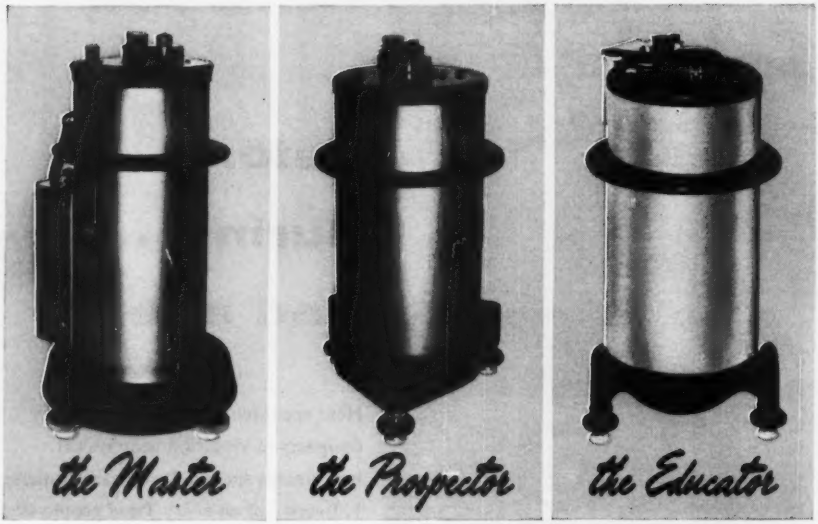

Now, you have a choice of three world-famous

TI WORDEN GRAVITY METERS

The MASTER retains the true portability and reliability for which the Worden Meter set a world precedent. However, the MASTER goes even further, having more demanding specifications plus a unique low-power temperature-stabilizing feature which together upgrade both the quantity and quality of gravity data. With the MASTER, in either severe or moderate temperature conditions, the absolute minimum number of base ties are required due to the positive linear drift, giving you a maximum production rate of the most accurate data at a reduced operating cost. The MASTER is truly the finest gravity meter available . . . with or without the temperature stabilizer in operation. Both the MASTER and PROSPECTOR have a gearless top reading dial which gives greater operator convenience and minimizes human error.

The PROSPECTOR has set reliability standards for gravity meters the world over. During the past ten years, over 450 of these gravity meters have been placed in use . . . this number exceeds the total of all other types combined. As with TI Worden Meters now in use, the PROSPECTOR will continue to provide exacting results in normal gravity programs. This is assured and even enhanced in that tighter manufacturing specifications have resulted in better temperature compensation and improved accuracy.

The EDUCATOR is designed to meet the needs of educational institutions, company training programs and surveys allowing for wider tolerances. This meter contains many of the outstanding features that have established Worden superiority, yet fulfills an increasing need for a reliable meter in limited budget projects.

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These, plus *many* more, are the reasons why you get the most with a Mayhew. 33 years of experience and engineering know-how are your guarantee of the very finest in all Mayhew equipment. There is a Mayhew rig for every job . . from the small versatile Model 200 to the largest 3000. Mayhew supply stores serve all oil areas with geophysical replacement parts and equipment, assuring continuous operation.

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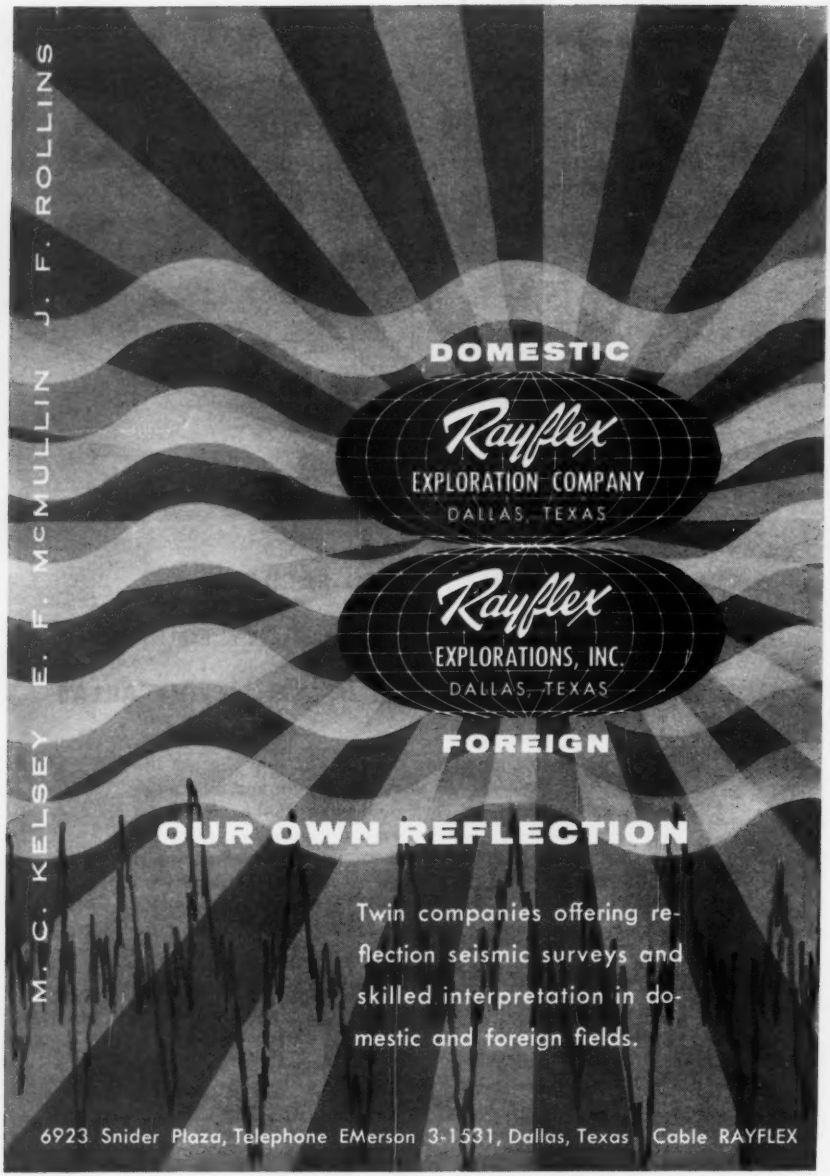
SO REMEMBER, WHEREVER YOU GO, YOU GET THE MOST WITH A MAYHEW!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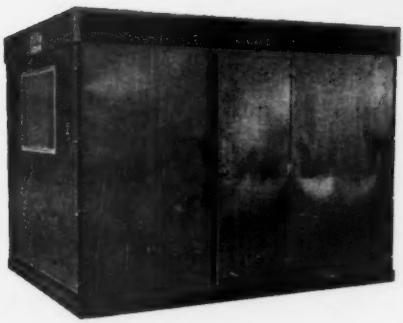
Model D-I-C $585 FOB plant
Size 10′ x 10′

- **Shipping case size— 40″ x 10′ x 14″**
- **Weight—550 lbs.**
- **Also available in size 10′ x 20′, model 2D-1-C**
- **Costs less than tents— let us prove it!**

Model D-I-C



Model K-10

$995 FOB plant
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- **Fully insulated**
- **Join several units together**
- **Weight—950 lbs.**
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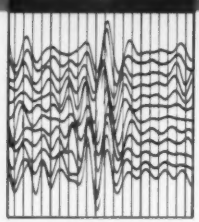
TWICE THE OUTPUT

S-23 Land Geophone

S-23M Marsh Geophone

Land (S-23) or Marsh (S-23M) ... Standard SIE high output geophones are fully guaranteed for two years!



An ordinary geophone and a 25 pound charge produced this record ... NOW — the new SIE S-23 double output geophone can produce the same record with as little as 5 pounds*— save as much as 20 pounds of dynamite!

Based on the physical relationship that amplitude of earth movement is proportional to the square root of the charge size.

75c *per month*
On Lease-Purchase Plan

LAND OR MARSH . . . HIGHEST SENSITIVITY OF ANY MINIATURE GEOPHONE

An entirely new magnetic structure achieves twice the sensitivity at no increase in weight and a reduction in cost. Standard S-23's have natural frequencies of 14, 18, 21, and 28 cps – other S-23's with natural frequencies of 7 to 75 cps are also available.

Remember that SIE offers complete cabling and stringing service. Write or call for more information.

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EUROPEAN FIRST

magnetic seismic recorder

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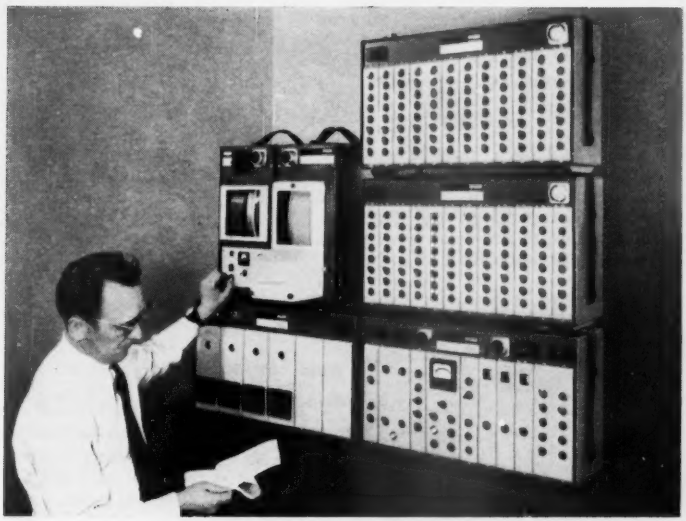

- 30-track magnetic-tape recording system: 24 seismic plus 6 auxiliary channels
- High sensitivity (*1 microvolt*) and wide response range (*1 to 220 cps*) permit both *reflection* and *refraction* methods of operation
- Features *unique gain control system:*
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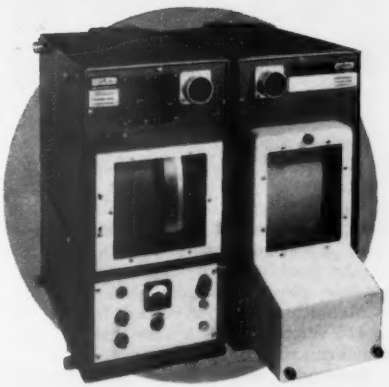

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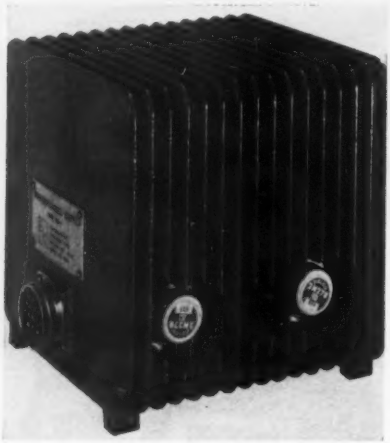
(Continued from page 53)

Signal attenuation due to the 50 microinch protective layer on sandwich tape does not significantly alter the tape's performance. Virtually identical playback wave patterns in these photographs of oscilloscope wave forms indicate both sandwich (bottom) and standard (open oxide) tapes are identical from a magnetic-electrical standpoint. There is no loss in pulse resolution up to 500 pulses per inch.

TRANSISTORIZED CONVERTERS

Designated the TS Series, these transistorized DC-DC converters will supply a continuous output of 200 watts. The compact, ruggedized fin-case design provides a high heat dissipation to size ratio, with a resulting efficiency of better than 85%. In-



advertent reversal of input polarity or a short across output will not damage the units. These units are ideal replacements for the troublesome dynamotor and vibrator-type power supplies. TS models are available in any input voltage from 6 vdc to 110 vdc, and with a wide range of customer-specified output voltages.

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PORTABLE ENGINE GENERATOR

"More power per pound and easily portable", is the way Mr. R. F. Weinig, Vice-President of **Wincharger Corporation, Sioux City 2, Iowa,** described the new Winco Lite portable engine generator. This compact portable power plant is rated at 2500-watts but develops up to 3000-watts A.C. Intermittent Power, yet weighs only

123 pounds with carrying handle. The Briggs & Stratton 4-cycle aluminum engine has service facilities nationwide.

The Winco Lite offers the many advantages of its exclusive AUTOMATIC CONSERV-er Idling Control, and FULL POWER at either voltage from one outlet, 115 V or 230 V. The control box contains one 15 ampere duplex receptacle and one 20 ampere 3-wire Twist-Lock receptacle, and one 20 ampere 2-wire Twist-Lock receptacle. Regularly equipped with Safe-T carrying handle as illustrated, the Winco Lite is also available with stationary base, a Speedy Shift 2-wheel dolly, or carrying cradle.

Wincharger Corporation, a subsidiary of Zenith Radio Corporation, manufactures a complete line of engine generators and tractor generators from 300 to 10,000 watts capacity for portable and standby power.

SA-100-1
SEISMIC AMPLIFIER

The SA-100-1 meets the requirements of present day geophysical exploration; its output, with filters out, is an exact amplified duplicate of the geophone signal. This seemingly simple function is made available to the industry, for the first time, in the SA-100-1.

(Continued on page 74)

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As subsurface knowledge increases,

As geological concepts are expanded and changed,

As geophysical analysis is sharpened,

Reviews of older surveys become increasingly productive.

How long since you last reviewed that magnetometer, gravimeter or even torsion balance survey of a presently active or potentially active area?

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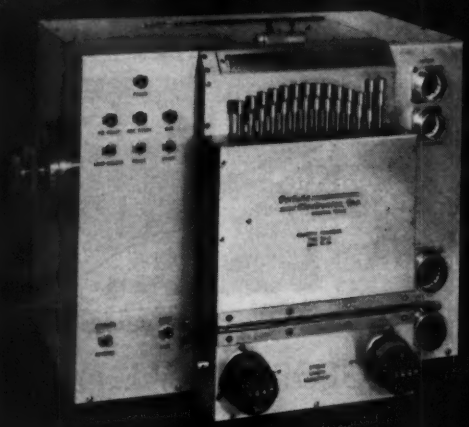

FORTUNE ELECTRONICS' DC-2

. . . the economical record-playback unit for office and field use

Fortune Electronics' new dynamic correction record-playback unit makes it possible for you to obtain accurate, corrected playbacks in the office or on location with a minimum initial investment. *The compact DC-2 handles any shot spread configuration. Spread length adjustments are calibrated directly in feet.* The unit accommodates standard six and one-half or seven inch tapes. Weighing only 82 pounds, the DC-2 is easy to handle—requires minimum space.

SPECIFICATIONS

Physical Characteristics	
Maximum Dynamic Correction	150 ms
Static Correction	±50 ms
Drive	400 cycle Hysteresis Motor Gear Coupled to Drum
Size	15 x 18 x 14 inches
Weight	82 pounds
No. of Traces	26 or 28
Electrical Characteristics	
Power Requirements	8 amperes @ 12 volts
Signal/Noise Ratio	50 db RMS to RMS
Timing Accuracy	±1 ms
Total Harmonic Distortion	2½% @ 100% Record Level
Crossfeed	—37 db @ 10 cycles

See Fortune's complete line of Geophysical Instruments on display in Booth 63, SEG Convention, November 9-12th, Los Angeles, California.

For complete details on the all new DC-2 write or call:

Fortune Electronics, Inc.

H. H. HAPPEL—H. H. HAPPEL, JR.
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The SIE on every package is your guarantee...

Your guarantee of fresh-from-the-factory recording supplies shipped in a matter of minutes — backed by a specialized quality control team that has been serving you for over 15 years!

Using SIE recording supplies, Every Shot Counts, because:

- **Tapes are de-magnetized and electronically checked.**
- **Each tape individually packed and serialized.**
- **Precision ruled recording charts are guaranteed accurate to thousandths.**
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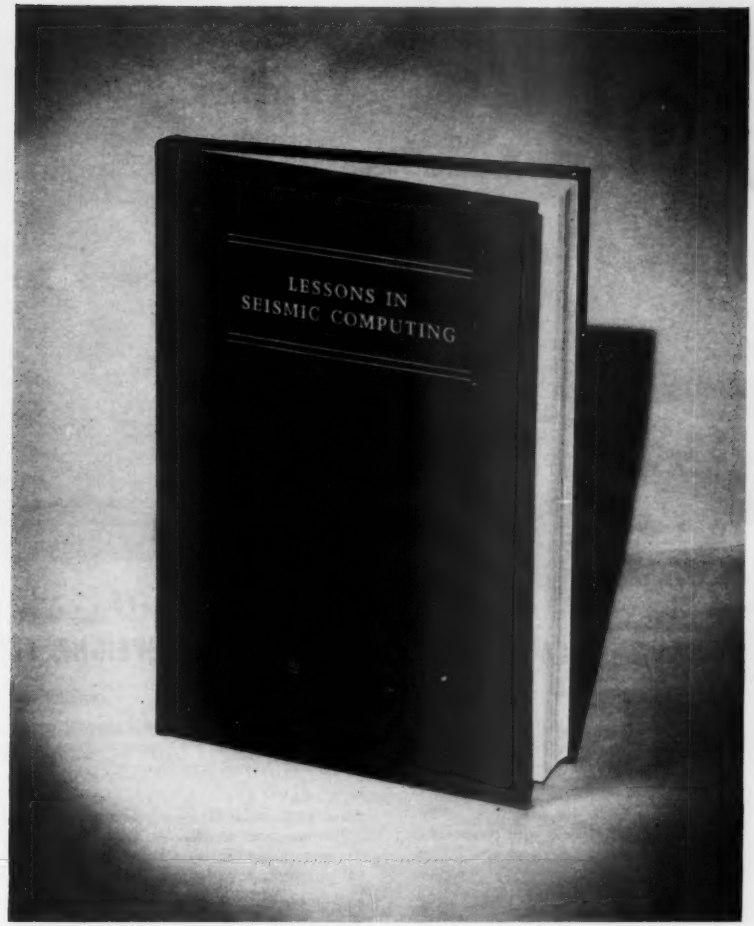

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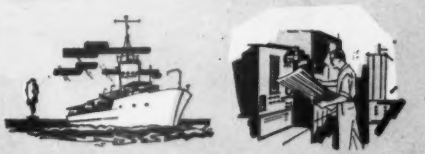

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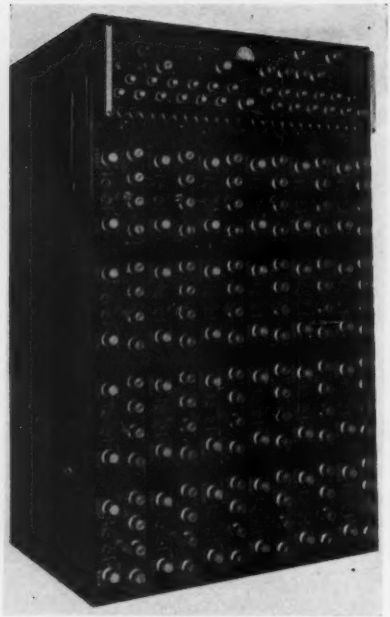
(Continued from page 64)



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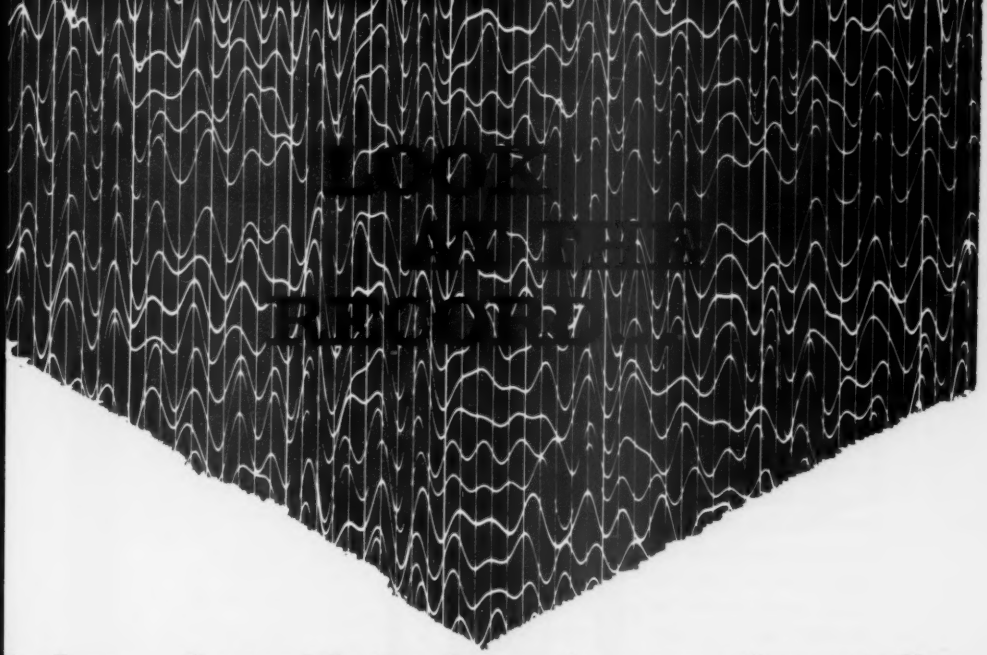
The McLean tester utilizes a photovoltaic cell or radio-active material as a source for the minute amount of electrical energy required.

MICRO-MINIATURE CIRCUITS

Melpar, Inc., a subsidiary of Westinghouse Air Brake Co., and a leader in the development of electronic equipment for the U. S. Government, recently announced that a special research program for the development of micro-miniature circuits which was begun last September has achieved success with the production of a new (15-in-1) micro-miniaturized electronic circuit.

(Continued on page 82)



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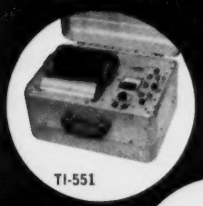

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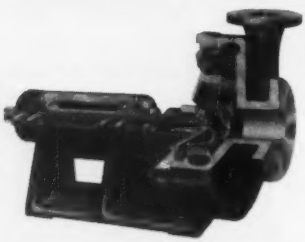

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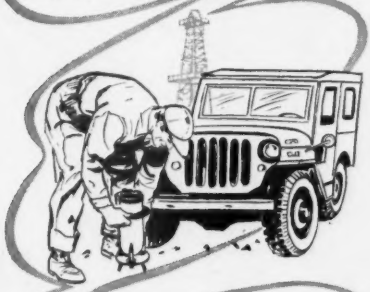

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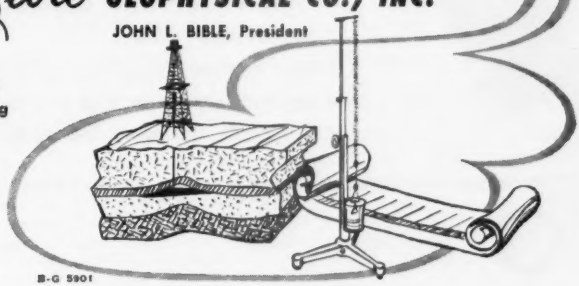

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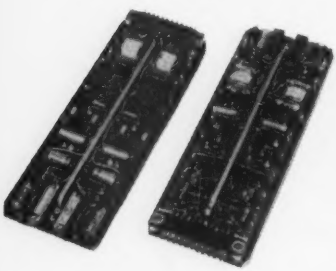

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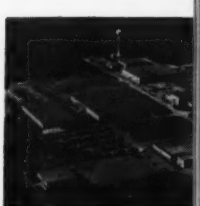

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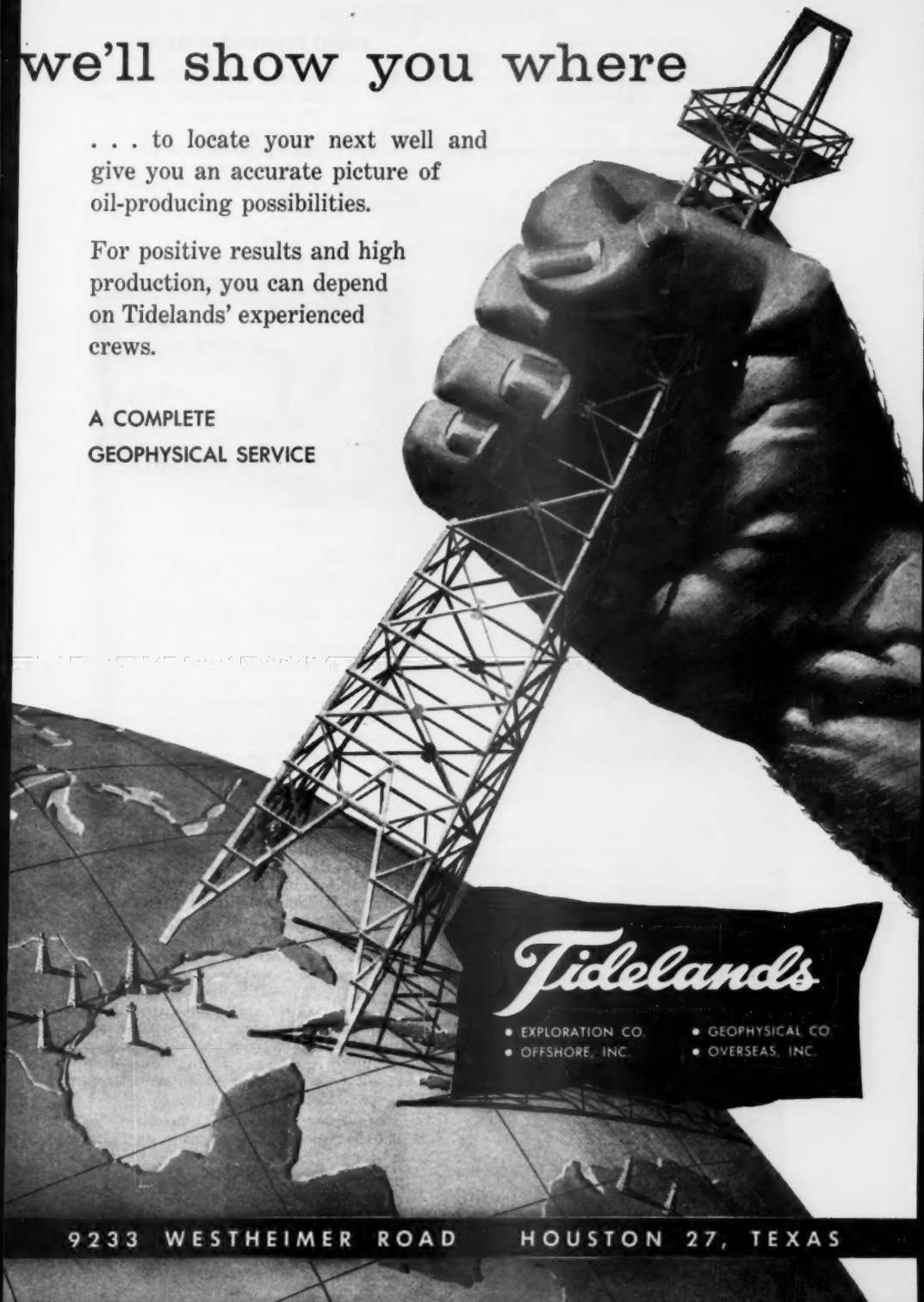

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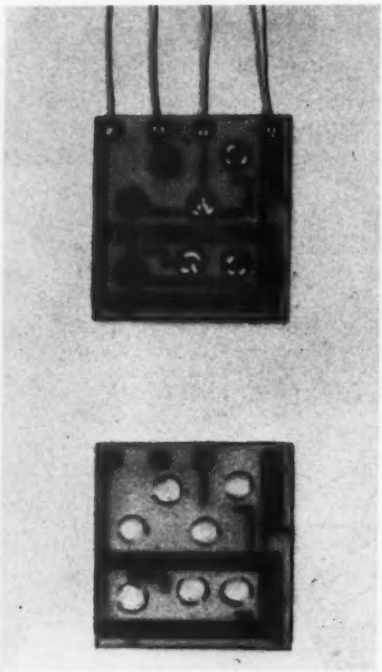
(Continued from page 74)

During the initial phase of the Melpar research project, a Chem. Lab. team directed by Physicist Stanley Bryla redesigned and built a workable miniature model of a standard computer circuit, a binary flip-flop.



This new micro-miniature circuit developed by Melpar, is so small that it can be hidden under a five cent coin, despite the fact that it contains 15 electronic components including: transistors, capacitors, diodes and resistors mounted on a ceramic base .625 inches square and .020 inches thick. It is considered potentially more reliable than its larger counterpart due to fewer connections, which reduce the possibility of failure.

The first Melpar micro-miniature circuit was built completely by hand with the aid of a microscope. Since then a micro-manipulator has been introduced to aid the precision positioning of the minute components which are part of these micro-miniature circuits.

Melpar, Inc., Falls Church, Virginia.

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SIE (Southwestern Industrial Electronics Co.), a division of Dresser Industries, Inc., announces the introduction of its new model ARP-2 Audio Response Plotter. The new ARP-2 provides permanent, pen-written frequency response curves of any audio range equipment quickly, easily and economically.

The ARP-2 not only eliminates costly hand-plotting methods, but will plot curves far too complex to be drawn by hand—such as the response of a loudspeaker in a live room. Other uses for the ARP-2 include operating it as a motor-driven audio oscillator and for plotting vibration curves of equipment tested on a shaking table. Circuitry is now included to allow the ARP-2 to be used as a 0 to 1 vdc recording voltmeter. The front panel is now slotted to permit the ARP-2 to be rack-mounted.

Input to the system under test is supplied by a continuous, single-sweep 20-20,000 cps audio oscillator in the ARP-2. As the oscillator sweeps its range, output signals from the test system are either fed directly to the Plotter or picked up by an optional condenser microphone. Records are plotted automatically on a 40 db-range logarithmic chart by a high-torque, servo-controlled, dry writing, pen recorder. The oscillator is directly connected to the recording drum to permit tracing, re-tracing or multiple recording of any portion of the curve, automatically or manually. A special input attenuator network enables the instrument to accept voltages up to 10 volts maximum, while input sensitivity is such that 40 db down from 10 mv yields quality records.

Southwestern Industrial Electronics Co., 10201 Westheimer Rd., Houston 19, Texas.

(Continued on page 90)

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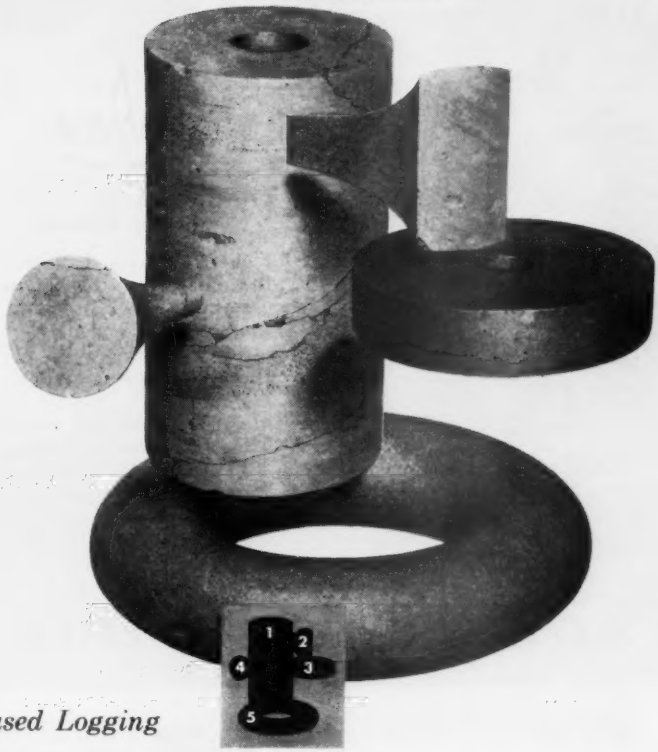

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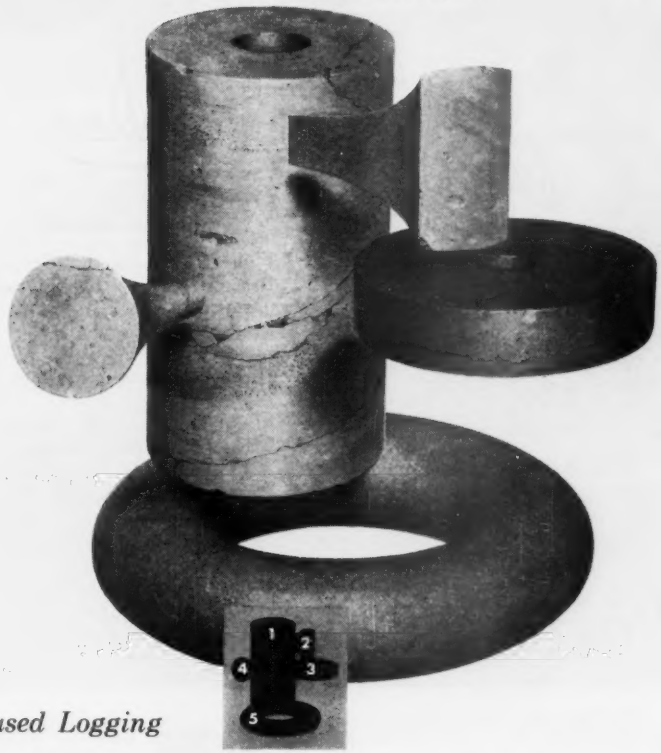

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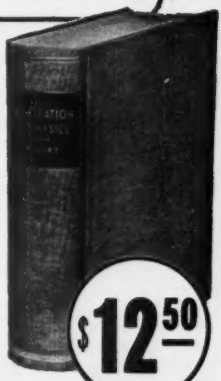

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(Continued from page 82)

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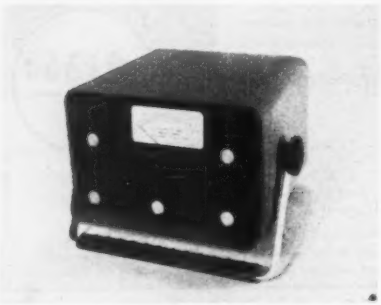
SIE (Southwestern Industrial Electronics Co.), a Division of Dresser Industries, Inc., Box 13058, Houston, Texas, announces the introduction of its new model T-1A Vibration Meter. The T-1A is a completely portable, battery powered, transistorized unit furnishing direct readings of the velocity, displacement amplitude and acceleration components of vibration, and, from a simple computation, its frequency. The T-1A has range and accuracy previously associated only with laboratory-type instruments.



The T-1A can accept up to six simultaneous transducer outputs—three for velocity-type pickups, three for crystal accelerometers—one output at a time being selected as desired. From the "Function" switch, it provides readings of up to 1000 g acceleration, 0.01-100 in./sec. velocity and 0.001-10 in. displacement at better than 5% overall accuracy. Plug-in, high-pass filters may be switched in to remove frequencies below 10, 15, 30, 70, 110, 150 and 200 cps. Output jacks on the T-1A permit it to be used with an oscilloscope or recorder for recording and monitoring vibration waveforms. The T-1A continues to feature the human-engineered appearance and functional ease of use pioneered by SIE in its Advanced Design Instrument line.

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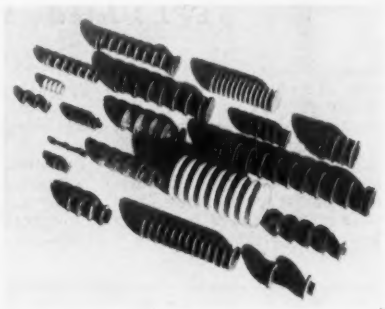

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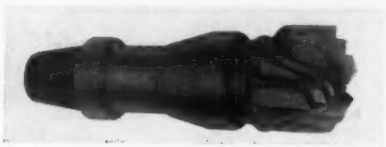

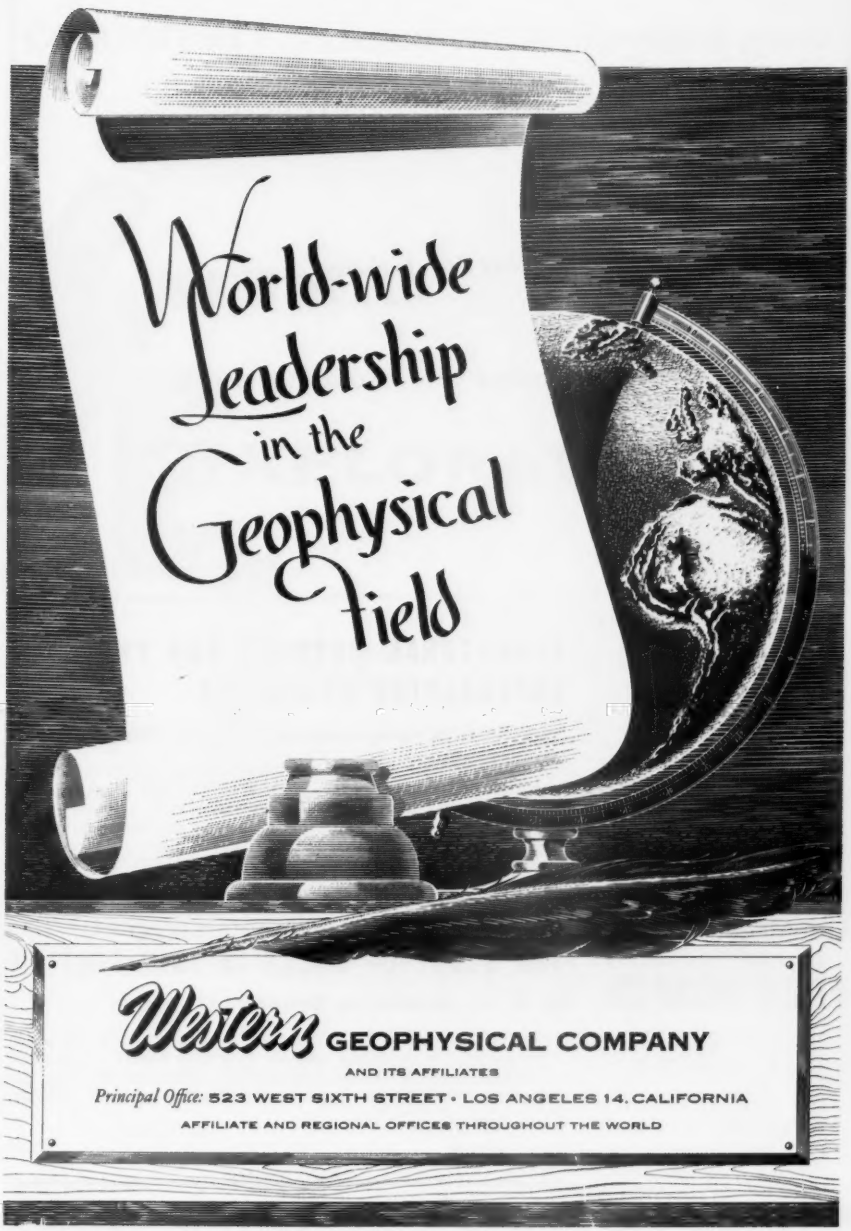
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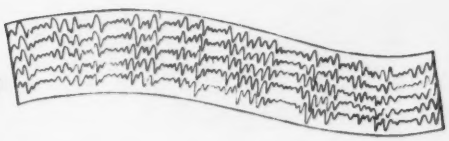

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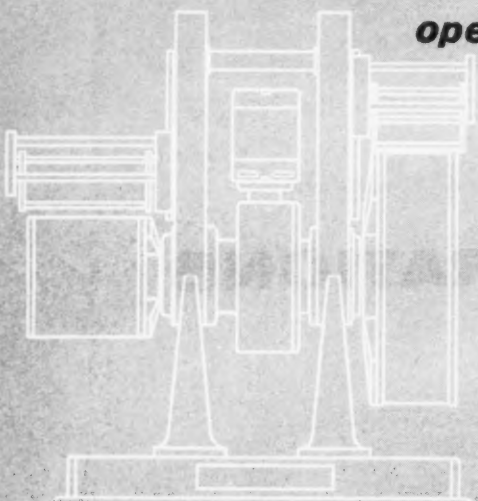

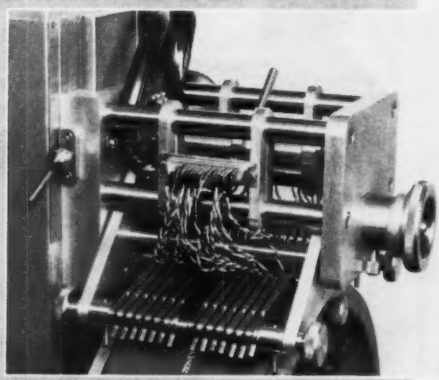

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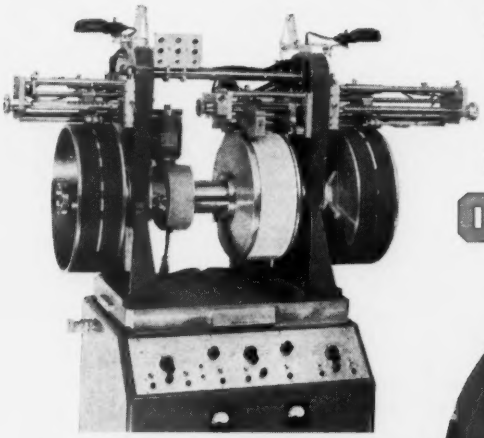
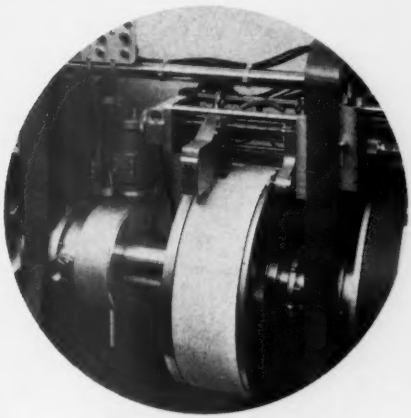


the Pen Monitor Assembly for the standard OMNITAPE



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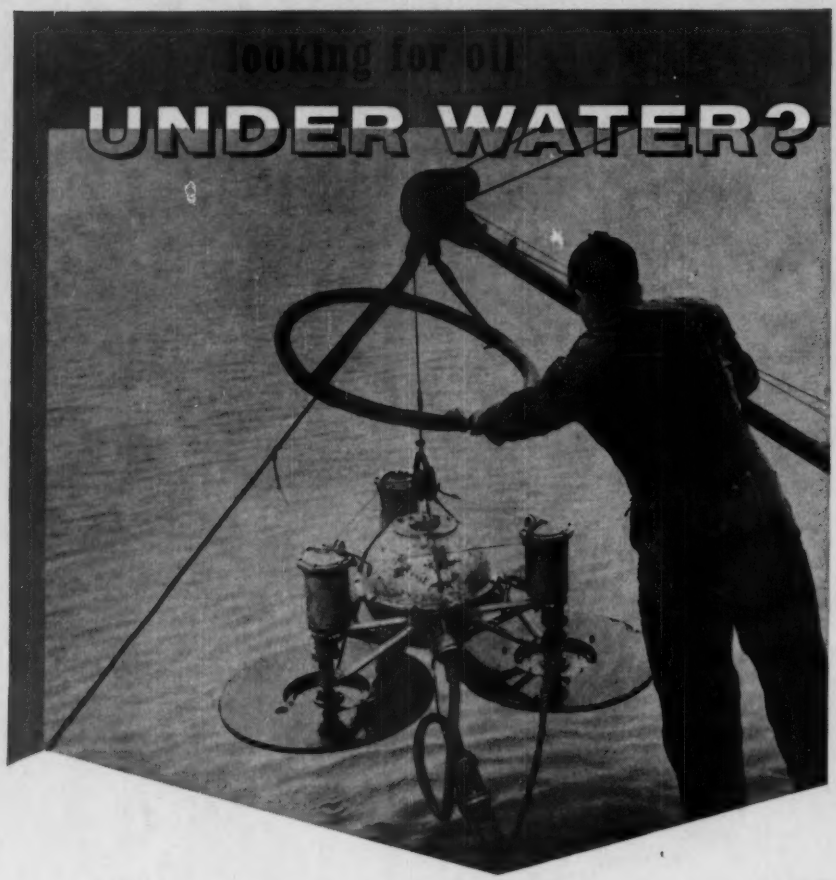

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